DRYING BY MEANS OF AIR AND STEAM

E. HAUSBRAND

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DRYING BY MEANS OF AIR AND STEAM

EXPLANATIONS, FORMULÆ AND TABLES FOR USE IN PRACTICE.

BY

E. HAUSBRAND

AUTHOR OF "EVAPORATING, CONDENSING AND COOLING APPARATUS"

TRANSLATED FROM THE GERMAN BY

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WITH TWO COLOURED DIAGRAMS, TWO ILLUSTRATIONS, AND THIRTEEN TABLES

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AUTHOR'S PREFACE.

THE theoretical principles, upon which are based the methods for calculating the dimensions of apparatus for drying wet material by means of air, are to be found in part in a number of text-books on Heat. All the formulæ and instructions in these books are, however, not quite suitable for immediate application.

It would not be quite sufficient for the practical scientist merely to give formulæ, more or less convenient, by means of which he could calculate the desired values for each case. In drying by means of air, which continually undergoes rapid and considerable changes in temperature and moisture, the conditions for the same apparatus may be so different at different times that one calculation, on the basis of one set of conditions, is not sufficient. The calculations should rather be made for several limiting cases; a procedure which is laborious and lengthy.

It is much more convenient to find the necessary values already calculated in tables, especially since a consideration of tabulated results gives an idea of the changes due to varying conditions, which cannot be obtained from isolated calculations made at random. When the effect, caused by alterations in all the relevant factors can be recognised without trouble, the whole arrangement can be properly planned. This is the only method by which the desired end can be attained with certainty.

From a consideration of the conditions for drying by means of air it is an easy step to a consideration of drying without air by steam alone. But I do not know that the circulating process of drying, as given in Chapter V. and Table XI., has been mentioned or discussed in any other place. I may, therefore, assume that these considerations are new. It is desirable that the advantages of this method should be known; it may then attain wide application.

From a clear appreciation of what has been said above arose the desire to furnish the means for determining the consumption of air and heat in a drying apparatus. May these pages often give help in need.

THE AUTHOR.

TRANSLATOR'S PREFACE.

The metric system of weights and measures, though not yet in general use in this country, has been retained in the translation. For purely educational purposes this system is, without doubt, more convenient; as regards practical applications, it did not appear that the conversion into British systems of the mass of figures involved would increase the utility of the book to a degree commensurate with the labour of transformation.

When the requirements of a drying apparatus are stated, and its dimensions have to be calculated, in terms of the British systems, the obvious course is to transform the data of the requirements into the metric system, perform the necessary calculations in that system by means of the Tables, and finally convert the ascertained dimensions, etc., of the apparatus into the British systems. On page vi will be found a comparison of the two systems of measurement, and of the Centigrade and Fahrenheit thermometer scales.

A. C. WRIGHT.

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THE METRIC AND BRITISH SYSTEMS.

TABLE OF COMPARISON.

Metres.	Deci-metres.	Centi-metres.	Milli-metres.	Inches.	Metres.	Deci-metres.	Centi-metres.	Milli-metres.	Inches.
·001	·01	·1	1	·039	·06	·6	6	60	2·362
·002	·02	·2	2	·079	·07	·7	7	70	2·756
·003	·03	·3	3	·118	·08	·8	8	80	3·150
·004	·04	·4	4	·157	·09	·9	9	90	3·543
·005	·05	·5	5	·197	·1	1	10	100	3·94
·006	·06	·6	6	·236	·2	2	20	200	7·87
·007	·07	·7	7	·276	·3	3	30	300	11·81
·008	·08	·8	8	·315	·4	4	40	400	15·75
·009	·09	·9	9	·354	·5	5	50	500	19·69
·01	·1	1	10	·394	·6	6	60	600	23·62
·02	·2	2	20	·787	·7	7	70	700	27·56
·03	·3	3	30	1·181	·8	8	80	800	31·50
·04	·4	4	40	1·575	·9	9	90	900	35·43
·05	·5	5	50	1·968	1	10	100	1,000	39·37

WEIGHT.

1 gramme = 15·44 grains.
28⅓ grammes = 1 oz. avord.
1 kilogramme = 1,000 ,, = 2·20 lb. avord.

LENGTH.

1 metre = 100 centimetres = 39·37 inches. Roughly speaking, 1 metre = a yard and a tenth. 1 centimetre = two-fifths of an inch. 1 kilometre = 1,000 metres = five-eighths of a mile.

VOLUME.

1 cubic metre = 1,000 litres = 35·32 cubic feet. 1 litre = 1,000 cubic centimetres = ·2202 gall.

HEAT.

1 calorie = 3·96 British thermal units.

COMPARISON BETWEEN FAHRENHEIT AND CENTIGRADE THERMOMETERS.

C.	F.	C.	F.	C.	F.	C.	F.	C.	F.
− 25	− 13	5	41	25	77	65	149	105	221
− 20	− 4	8	46·4	30	86	70	158	110	230
− 17	1·4	10	50	35	95	75	167	115	239
− 15	5	12	53·6	40	104	80	176	120	248
− 10	14	15	59	45	113	85	185	125	257
− 5	23	17	62·6	50	122	90	194	130	266
0	32	18	64·4	55	131	95	203	135	275
1	33·8	20	68	60	140	100	212	140	284

To Convert:—

Degrees C. to degrees F., multiply by 9, divide by 5, then add 32.
Degrees F. to degrees C., first subtract 32, then multiply by 5 and divide by 9.

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DRYING BY MEANS OF AIR AND STEAM.

CHAPTER I.

INTRODUCTION.

In many industries it is necessary to dry the principal or subsidiary products by means of air which is artificially heated before use.

There are many reasons for using air as an intermediary in abstracting moisture from materials, instead of heating the substances directly, either at atmospheric pressure or *in vacuo*, and so evaporating the water.

Air-drying is preferred, because the condition and nature of the wet material make it difficult to convey the necessary amount of heat directly to its particles, or because the substance to be dried cannot be heated beyond a certain low temperature, since it would otherwise be injured in shape, appearance or composition, or, finally, because it is desired to effect the drying slowly by gradual evaporation, in order to avoid tears, cracks or discoloration.

The air which is used for drying must *first* heat the wet material, *then* communicate to it the heat necessary to evaporate the water, and, *finally*, absorb the evaporated water.

The heated air which enters the drying chamber loses therein the quantity of heat required for heating and evaporation; thus it always leaves the drying-room at a temperature lower than that at which it entered. But it must at its exit be so much hotter than at its entry into the heating chamber that it is able to retain the evaporated water together with its original moisture without being supersaturated.

Atmospheric air always contains more or less moisture, but is rarely saturated. Its capacity of taking up water increases rapidly with increasing temperature. In order that the smallest possible quantity of air may carry the largest possible quantity of water from the drying-room, it must leave the room at the highest feasible temperature. On the other hand, this same quantity of air must be so much hotter, when it enters the drying-room, that its cooling to the outlet temperature is sufficient to heat the wet material and to evaporate the water in the latter.

Since the expenditure of heat in drying by means of air is equal to that required to heat the air, it follows that the less heat is necessary the less air is used. The least quantity of air is required when it is at the highest permissible temperature both at entry and exit.

The temperature, to which the air may be heated before its entry, depends on the nature of the material and on the extent to which it is to be freed from moisture.

If the material is to be completely dried, it must finally be heated almost to the temperature of the entering air; thus, in this case, the air may be heated only to the highest temperature which the material can bear.

However, if the material may still contain considerable quantities of moisture after drying, it is not requisite to heat it by means of the air to the temperature of the latter. The temperature of the entering air may then be made somewhat higher than in the previous case.

In each separate case the following quantities must be supposed to be known :—

1. The weight of the material to be dried.
2. The quantity of water to be extracted from the material.
3. The highest temperature to which the material can be exposed.

It is desired to find—

1. The quantity of heat which must be used.
2. The heating surface which will be required.
3. The requisite volume of air, *i.e.*, the volume *before* heating, *after* it is heated, and *at* its exit from the apparatus.

The question may also arise whether it is desirable to apply in the drying-room a pressure higher or lower than that of the atmosphere.

In the following pages the answers to these questions are worked out in the simplest possible manner and presented in a form suitable for application to a number of cases in practice.

Air changes its volume under the influences of pressure and temperature. A cubic metre of air introduced into the calculation must be defined as at a certain temperature and pressure so that it may again be recognised.

If it be calculated how much heat a certain volume of air at a definite temperature and pressure can give out, and how much moisture it can take up, it will be found that after the air has done this work, *i.e.*, after it has given out heat and taken up moisture, its volume will be quite different. This new volume must then be again calculated. These calculations cannot be done without some practice, and in any case require time and trouble. It is therefore preferable —and one's ideas soon become accustomed to the change— to introduce the weight of the air instead of the volume into the calculation, and finally to convert the weight found into volumes, if required.

It will be found that the calculations to be made in each case are not difficult. They require, however, a certain insight into the matter, which there is not always time to acquire in practice. Also, the effect of an alteration in the different conditions under consideration cannot at once be estimated *à priori* with accuracy. But when the effect exerted by variations in pressure, temperature and saturation upon the output and the expenditure of air and heat, can be seen at a glance, the best conditions can readily be chosen. For these reasons the requirements of drying installations of different kinds have been collected into tables, from which the desired data can at once be gathered in every case.

Allowances must be made in practice for losses of quantity, weight and heat.

In the first place a table will be calculated showing how much water can be taken up by 1 kilo. of air at different temperatures and pressures.

The weight of air of certain pre-determined initial temperatures will then be found, which is the least quantity required to take up a certain weight of water (100 kilos.).

The volumes will also be given which are occupied by the calculated weight of air at its entry and exit and after it has been heated.

Finally will follow the calculation of the quantity of heat required for evaporating a certain weight of water. This quantity varies greatly according to the conditions. The calculation of the necessary heating surface and the width of the flues will then be appended.

All these calculations have to be made for drying at the atmospheric pressure and at lower or higher pressures, and under the supposition of a more or less complete saturation of the air which enters and leaves the drying apparatus.

The symbols used throughout the book are as follows:—

w = the weight of water, which is to be withdrawn from the material in the drying-room.
v = the volume, in litres, of 1 kilo. of water vapour.
V_d = the volume, in cubic metres, of any other weight of vapour.
k_d = the weight, in kilos., of 1 cubic metre of vapour.
d_a = the weight, in kilos., of vapour contained in 1 kilo. of the external air.
d_n = the weight, in kilos., of vapour contained in 1 kilo. of the wet air which leaves the apparatus.
k_l = the weight, in kilos., of 1 cubic metre of dry air.
l = the weight of air in kilos.
V_l = the volume of air in cubic metres.
V_{la} = the volume of the (atmospheric) external air in cubic metres.
V_{lh} = the volume of the hot air when it is just leaving the heating chamber.
V_{ln} = the volume of the wet air when it leaves the drying-room.
t_u = the original temperature of the material to be dried.
t_z = the temperature of the material when it leaves the drying room.
t_a = the temperature of the external air.
t_h = the temperature of the hot air just as it is leaving the heating chamber.
t_n = the temperature of the wet air when it leaves the drying-room.
p = the pressure, in atmospheres or in kilos. per square metre (1 atmosphere = 10,336 kilos. per square metre).
q = the pressure in millimetres of mercury.
e = the co-efficient of expansion of air = 0·003665.
C_n = the quantity of heat, in calories, required to evaporate the water from the material.
C_g = the total quantity of heat which must be used.

$$\left.\begin{array}{l} r = \text{the specific heat of air} = 0{\cdot}2375 \\ s = \text{the specific heat of steam} = 0{\cdot}475. \end{array}\right\}\text{ at constant pressure.}$$

CHAPTER II.

Calculation of the Maximum Weight of Saturated Aqueous Vapour which can be contained in 1 Kilo. of Air at different Pressures and Temperatures.—Table I.

According to a well-known physical law saturated water vapour has a definite pressure at each temperature, whether it is in space empty of, or filled with, air. Thus, in speaking of air saturated with moisture, we mean that in the space which contains the air there is just as much saturated water vapour as would be contained in it, at the same temperature, if no air were present. The pressure, which this saturated vapour exerts at particular temperatures, is quite definite and well known. It has been found by numerous experiments, the results of which have been arranged in tables by Regnault, Zeuner and Fliegner. At temperatures below 100° C. it is always less than the pressure of the atmosphere, and the pressure of the atmosphere is produced by adding the pressure of the air to the pressure of the aqueous vapour. The atmospheric pressure is thus composed of the partial pressures of the vapour and the air—it is the sum of the two.

The greatest weight of saturated water vapour which can be contained in 1 cubic metre at a certain temperature is, according to the above physical law, the same whether air is also present in the cubic metre or water vapour alone fills the space. Thus it follows that the weight of 1 cubic metre of saturated water vapour, which is to be obtained from the tables constructed by the above physicists, also gives the maximum weight of water contained in 1 cubic metre of air at the different temperatures.

1 cubic metre of water vapour at 0° C. weighs 0·00504 kilos.
,, ,, 5° C. ,, 0·00696 ,,
,, ,, 10° C. ,, 0·00951 ,,
,, ,, 15° C. ,, 0·01319 ,,
,, ,, 20° C. ,, 0·01753 ,,

The same weights of vapour are contained by 1 cubic metre of air when it is saturated with moisture.

When the air is completely saturated with water vapour we say that its degree of saturation is 100 per cent. If it contains less moisture, *e.g.*, only $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ as much, we say that its degree of saturation is 75, 50 or 25 per cent.

Thus 1 cubic metre of air contains the following weights of water at the temperatures given :—

Degree of Saturation.	0° C.	5° C.	10° C.	15° C.	20° C.
Per cent.	Kilos.	Kilos.	Kilos.	Kilos.	Kilos.
10	0·000504	0·000696	0·000951	0·001319	0·001753
20	0·00101	0·00139	0·00191	0·00264	0·00351
50	0·00252	0·00345	0·00475	0·00660	0·00877

The volume of vapour v, in litres, which is evolved from 1 kilo. of water is found from the formula of Mariotte, Boyle and Gay-Lussac—

$$v = 4{\cdot}543\,\frac{273 + t^{*}}{p}, \quad \ldots\ldots\ldots \quad (1)$$

where t is the temperature and p the pressure in atmospheres.

The weight of 1 cubic metre of saturated vapour is therefore—

$$k_d = \frac{1}{v} = \frac{p}{4{\cdot}543\,(273 + t)}. \quad \ldots\ldots\ldots \quad (2)$$

---

* $273 + t$ is called the *absolute* temperature.

Almost the same results, as are given by calculating according to these equations, are obtained in another way. The density of saturated vapour is 0·623, referred to air = 1. The weight of 1 cubic metre of vapour is thus always 0·623 of the weight of 1 cubic metre of dry air at the same temperature and pressure. Thus, when the weight of 1 cubic metre of dry air is calculated for all temperatures and pressures, and the result multiplied by 0·623, the weight of 1 cubic metre of saturated vapour is obtained. The figures calculated in this way agree almost exactly with those derived from equation (2).

The pressure p of saturated water vapour at all temperatures is sufficiently well known through the observations and tables of Regnault, Zeuner and Fliegner; also the weight of 1 cubic metre, k_d.

The second column of Table I. (pp. 10-11) gives the weight of 1 cubic metre of saturated vapour, the third column the pressure of saturated vapour in millimetres of mercury, according to Regnault, both at the temperatures in the first column.

The atmospheric pressure varies between tolerably wide limits. In Table I. barometric heights of 780, 760 and 740 mm. are considered, and in columns 4, 5 and 6 the partial pressure is given which is exerted by the air itself, independently of the pressure of the saturated vapour, at these pressures and temperatures from – 20° to + 100° C. The partial pressure of the air is equal to the barometric pressure *minus* the pressure of the vapour.

In columns 7, 8 and 9 the weights of 1 cubic metre of dry air is given, at the pressures in the columns 4, 5 and 6, and temperatures from – 20° to + 100° C.

The weight of 1 cubic metre of dry air is calculated from the formula—

$$k_l = \frac{0{\cdot}0001252}{1 + et} \, \frac{qp}{760}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which k_{t} is the weight of the air in kilos., t is the temperature in centigrade degrees, p is the atmospheric pressure in kilos. per square metre (= 10,336), q is the (partial) pressure supported by the air alone, and e is the co-efficient of expansion of air (= 0·003665).*

The atmospheric pressure, p, upon 1 square metre is 10,336 kilos. when the barometer stands at 760 mm.; for any other barometric height, q,—

$$p = \frac{q}{760}\,10336. \qquad \qquad (4)$$

If the pressure of the vapour in the atmosphere be deducted from the barometric pressure in millimetres of mercury at the moment, the remainder is the pressure supported by the air alone.

By means of a simple calculation from the figures in columns 2 to 9, the maximum weight of saturated vapour is found, which 1 kilo. of air initially dry can contain at various temperatures and pressures. It is only necessary to divide the weight of 1 cubic metre of saturated vapour by the weight of 1 cubic metre of dry air at the same temperature and the corresponding pressure. The results of these calculations are contained in columns 10, 11 and 12.

The columns 13 to 21 of Table I. give corresponding data for absolute pressures of 1½ atmospheres (½ atmosphere above the ordinary pressure), ⅓ and ⅔ atmosphere, equal to 1,140, 250 and 500 mm. of mercury respectively.

The figures of columns 13, 16 and 19 are found by subtracting the vapour pressure of column 3 from the assumed total pressures 1,140, 250 and 500 mm.

The numbers in columns 14, 17 and 20 are obtained from equation (3) by inserting the corresponding values for q and t.

* This is $\frac{1}{273}$

TABLE

Pressures and Weights of 1 cubic metre of

The Weight of Water in 1 kilo. of Air at the absolute (barometric) from – 20° to + 100° C., when the air

1	2	3	4	5	6	7	8	9	10	11
Temperature.	Weight of 1 Cubic Metre of Saturated Vapour, k_d.	Pressure of the Saturated Vapour, q_d.	(Partial) Pressure of the Air alone, after Subtraction of the Vapour Pressure, at the Barometric Heights of			Weight of 1 Cubic Metre of *Dry* Air, at the Pressures in Columns 4, 5 and 6, and at the Barometric Heights of			Weight of *saturated* *d*, contained by 1 dry air at the in Columns 4, 5 and the barometric of	
°C.	Kilos.	Mm.	780 Mm.	760 Mm.	740 Mm.	780 Kilos.	760 Kilos.	740 Kilos.	780 Kilos.	760 Kilos.
–20	0·00106	0·927	779·0	759·0	739·0	1·4256	1·3890	1·3524	0·000743	0·000763
–15	0·00157	1·400	778·6	758·6	738·5	1·4015	1·3655	1·3294	0·00112	0·00115
–10	0·0023	2·093	778·0	758·0	738·0	1·3739	1·3386	1·3033	0·00167	0·00172
– 5	0·0035	3·113	776·9	756·9	736·9	1·3518	1·3178	1·2823	0·00248	0·00254
0	0·00496	4·600	775·4	755·4	735·4	1·3181	1·2832	1·2502	0·00376	0·00387
5	0·00696	6·53	773·47	753·47	733·47	1·2925	1·2589	1·2257	0·00538	0·00553
10	0·00951	9·16	770·84	750·84	730·84	1·2642	1·2332	1·1987	0·00752	0·00771
15	0·01298	12·70	767·3	747·3	727·3	1·2354	1·2050	1·1709	0·0105	0·01080
20	0·01753	17·39	762·61	742·61	722·61	1·2087	1·1770	1·1453	0·0145	0·01480
25	0·02312	23·55	756·46	736·46	716·46	1·1755	1·1445	1·1134	0·0197	0·0202
30	0·0308	31·55	748·45	728·45	708·45	1·1423	1·1168	1·0861	0·02696	0·0275
35	0·0397	41·83	738·17	718·17	698·17	1·1146	1·0845	1·0543	0·0356	0·0366
40	0·0512	54·91	725·09	705·09	685·09	1·0760	1·0463	1·0207	0·0476	0·0489
45	0·0657	71·40	708·60	688·6	668·6	1·0346	1·0054	0·9751	0·0635	0·0653
50	0·0834	91·98	688·02	668·02	648·02	0·9894	0·9610	0·9318	0·0843	0·0868
55	0·1045	117·98	662·52	642·52	622·52	0·9355	0·9070	0·8797	0·1117	0·1152
60	0·1311	148·79	631·21	611·21	591·21	0·8774	0·8497	0·8219	0·1495	0·1540
65	0·1623	186·94	593·06	573·06	553·06	0·8156	0·7880	0·7605	0·1989	0·2060
70	0·1992	233·09	546·91	526·91	506·91	0·7383	0·7115	0·6844	0·2696	0·2799
75	0·2440	288·50	491·50	471·50	451·50	0·6562	0·6295	0·6027	0·3718	0·387
80	0·2958	354·64	425·56	405·56	385·56	0·5600	0·5335	0·5018	0·5282	0·554
85	0·3574	433·04	346·96	326·96	306·96	0·4510	0·4250	0·3991	0·7924	0·840
90	0·4280	525·45	254·55	234·55	214·55	0·3248	0·2992	0·2747	1·3177	1·430
95	0·5110	633·75	146·25	126·25	106·25	0·1846	0·1591	0·1340	2·7681	3·211
100	0·6060	760·00	20·00	0	—	0·0249	0	—	24·3373	—

I.

Saturated Water Vapour and of Dry Air.

pressures of 250, 500, 740, 760, 780 and 1,140 mm., and at temperatures is *completely saturated* with vapour.

12	13	14	15	16	17	18	19	20	21	22
vapour, kilo. of pressures 6, and heights	Absolute Pressure in Drying-room, 1½ atmos. = 1,140 mm.			Absolute Pressure in Drying-room = 500 mm.			Absolute Pressure in Drying-room = 250 mm.			
740 Kilos.	Pressure of the Air after Subtraction of the Vapour Pressure, q_l. Mm.	Weight of 1 Cubic Metre of Dry Air, k_l. Kilos.	Weight of Saturated Vapour, d, in 1 Kilo. of Air. Kilos.	Pressure of the Air after Subtraction of the Vapour Pressure, q_l. Mm.	Weight of 1 Cubic Metre of Dry Air, k_l. Kilos.	Weight of Saturated Vapour, d, in 1 Kilo. of Air. Kilos.	Pressure of the Air after Subtraction of the Vapour Pressure q_l. Mm.	Weight of 1 Cubic Metre of Dry Air, k_l. Kilos.	Weight of Saturated Vapour, d, in 1 Kilo. of Air. Kilos.	Temperature. °C.
0·000783	1139·0	2·084	0·00050	499·07	0·91	0·00165	249·07	0·455	0·00233	–20
0·00118	1138·6	2·049	0·00076	498·6	0·8974	0·00175	248·6	0·447	0·00351	–15
0·00176	1138·38	2·008	0·00115	497·90	0·877	0·00262	247·9	0·438	0·00525	–10
0·00261	1136·9	1·978	0·00169	496·88	0·862	0·00386	246·89	0·429	0·0078	– 5
0·00396	1135·4	1·930	0·00257	495·4	0·842	0·00589	245·4	0·417	0·0119	0
0·00566	1133·47	1·894	0·00367	493·47	0·8225	0·00846	243·47	0·407	0·0171	5
0·00795	1130·84	1·854	0·00513	490·84	0·805	0·0118	240·84	0·395	0·0240	10
0·0110	1127·3	1·815	0·00709	487·3	0·785	0·0165	237·3	0·382	0·0340	15
0·0153	1122·6	1·779	0·00981	482·61	0·765	0·0229	232·6	0·378	0·0464	20
0·0207	1116·5	1·735	0·0134	476·45	0·740	0·0312	226·45	0·352	0·0656	25
0·0283	1108·5	1·699	0·0181	468·45	0·718	0·0429	218·45	0·335	0·0919	30
0·0376	1098·2	1·658	0·0239	458·17	0·692	0·0573	208·17	0·314	0·1264	35
0·0501	1085·1	1·610	0·0318	445·09	0·660	0·0776	195·09	0·287	0·1784	40
0·0673	1068·6	1·560	0·0421	428·6	0·626	0·1049	178·6	0·261	0·2517	45
0·0895	1049·0	1·508	0·0553	408·02	0·586	0·1423	158·02	0·227	0·3674	50
0·1185	1022·5	1·444	0·0723	382·52	0·539	0·1939	132·52	0·187	0·5588	55
0·1590	991·2	1·378	0·0951	351·21	0·488	0·2685	101·21	0·141	0·9300	60
0·2130	953·1	1·311	0·1239	313·06	0·430	0·3774	63·06	0·0867	1·877	65
0·2915	897·0	1·211	0·1644	266·91	0·360	0·533	16·91	0·0228	8·737	70
0·4050	851·5	1·133	0·2153	211·5	0·282	0·865	—	—	—	75
0·5890	785·4	1·033	0·286	145·36	0·191	1·548	—	—	—	80
0·894	707·0	0·919	0·388	66·96	0·087	4·108	—	—	—	85
1·557	614·5	0·784	0·546	—	—	—	—	—	—	90
3·813	506·25	0·638	0·8009	—	—	—	—	—	—	95
—	380·0	0·473	1·281	—	—	—	—	—	—	100

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Finally, the weight of water vapour contained in 1 kilo. of air at the various pressures is obtained by dividing the weights in columns 14, 17 and 20 into the corresponding figures in column 2.

Examples. It is required to estimate—

1. The weight of 1 cubic metre of dry air, which is saturated with moisture, at the temperature $t_a = 10°$ C., and the barometric pressure, $q = 760$ mm. (column 8).

2. The weight of water vapour, d_a which is contained in 1 kilo. of air in this case (column 11).

3. The weight of 1 cubic metre of dry air, which is saturated with moisture, at $t_a = 10°$ C. and the absolute pressure $q = 250$ mm. (column 20).

4. The weight of water vapour which is contained in 1 kilo. of air in Example 3.

Ex. 1. According to equation (3)—

$$k_l = \frac{0{\cdot}0001252}{1 + et}\,\frac{qp}{760},$$

where q is the partial pressure of the air in the cubic metre, being the difference between the total pressure of the air (in this case 760 mm.) and the pressure of saturated vapour at 10° C. (9·16 mm. according to column 3). Therefore—

$$q = 760 - 9{\cdot}16 = 750{\cdot}84 \text{ mm.},$$

whence

$$\frac{qp}{760} = \frac{750{\cdot}84 \times 10336}{760} = 10211{\cdot}4,$$

and

$$k_l = \frac{0{\cdot}000152 \times 10211{\cdot}4}{1 + 0{\cdot}003665 \times 10} = 1{\cdot}2332 \text{ kilos. (see column 8).}$$

Ex. 2. Thus 1 cubic metre contains, at 10° C. and 760 mm. pressure, 1·2332 kilos. of air and (from column 2) 0·00951 kilo. of water vapour. In 1 kilo. of air there is, therefore, in this case—

$$\frac{0{\cdot}00951}{1{\cdot}2332} = 0{\cdot}00771 \text{ kilo. of vapour (column 11).}$$

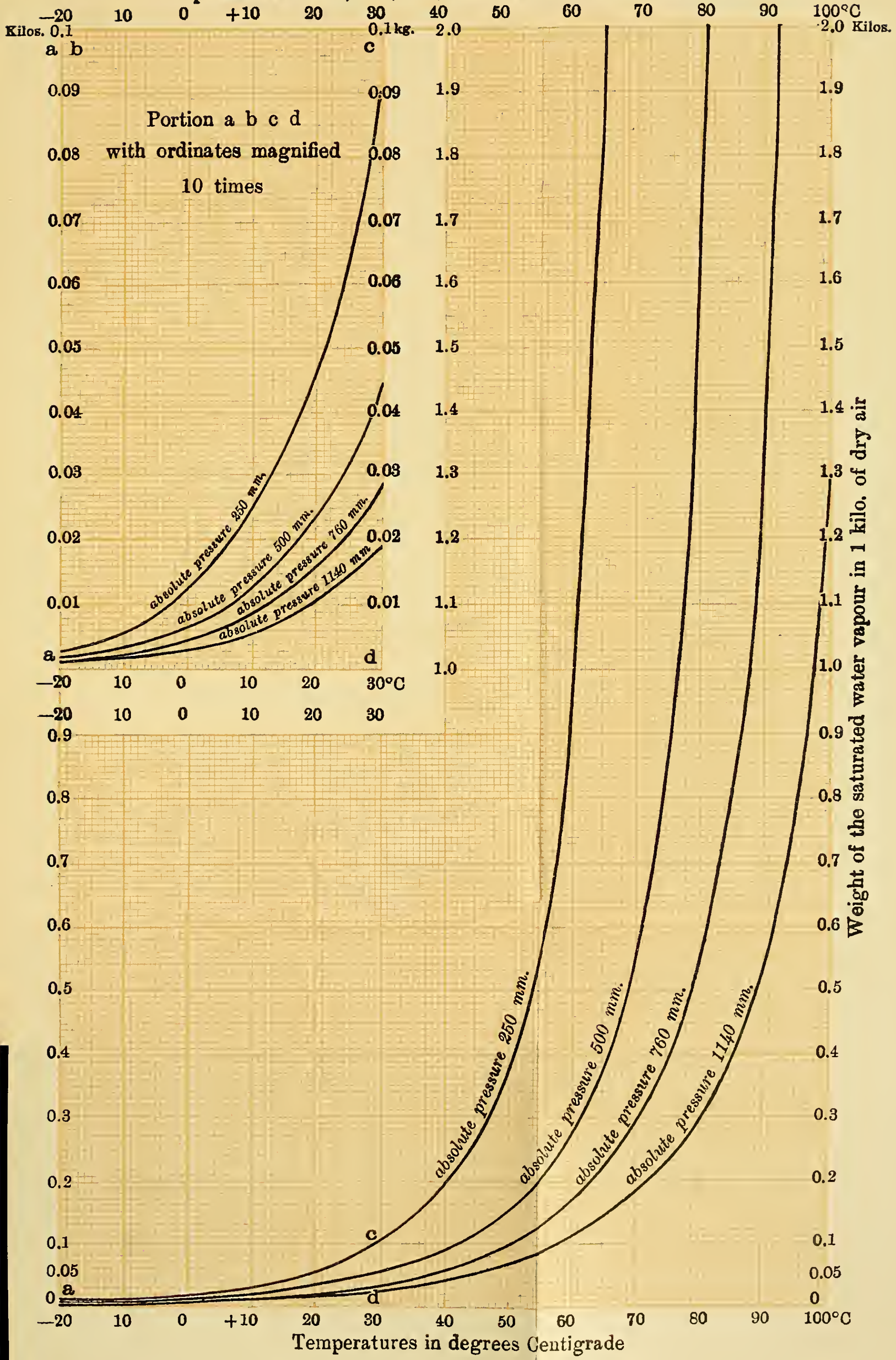
Ex. 3. In equation (3)

$$t_a = 10° \text{ C.}, \qquad e = 0{\cdot}003665, \qquad q = 250 - 9{\cdot}16 = 240{\cdot}84$$

$$\frac{qp}{760} = \frac{240{\cdot}84 \times 10336}{760} = 3275{\cdot}4.$$

Diagram I.

The weight of saturated water vapour capable of absorption by 1 kilo. of dry air at different temperatures and at the absolute pressures of 250, 500, 760, and 1140 mm of mercury.



Hausbrand's Drying by means of Air and Steam.

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Therefore—

$$k_l = \frac{0{\cdot}0001252 \times 3275{\cdot}4}{1 + 0{\cdot}003665 \times 10} = 0{\cdot}395 \text{ kilo. (column 20).}$$

Ex. 4. Thus 1 cubic metre of air contains, at 10° C. and 250 mm. absolute pressure, 0·395 kilo. of air and (column 2) 0·00951 kilo. of vapour.

Therefore 1 kilo. of air contains—

$$\frac{0{\cdot}00951}{0{\cdot}395} = 0{\cdot}024 \text{ kilo. of vapour (column 21).}$$

From Table I. (see pp. 10 and 11) it may readily be seen that 1 kilo. of air can carry the more saturated vapour the hotter it is itself and the lower is the pressure.

The accompanying Diagram I. represents the results contained in columns 11, 15, 18 and 21. It shows the weight of saturated water vapour which can be taken up by 1 kilo. of air at the absolute pressures 250, 500, 760 and 1,140 mm., and at temperatures from – 20° to + 100°. Nothing new is to be obtained from this diagram, but it is convenient to be able to see at a glance how the absorption of vapour by air varies according to the temperature and pressure.

With the assistance of Table I. we can now calculate the quantities of air and heat required to evaporate a certain weight of water under various conditions.

CHAPTER III.

Calculation of the Necessary Weight and Volume of Air, and of the Least Expenditure of Heat, for Drying Apparatus with Heated Air, at Atmospheric Pressure.

A.—*With the assumption that the air is* completely saturated *with vapour both before entry and at its exit from the apparatus.*—Table II.

Atmospheric air is seldom completely saturated with vapour. The degree of saturation varies from 10 to 100 per cent., and frequently changes in the course of a single day to the extent of 50 to 60 per cent. Thus, in calculating the weight of air necessary to accomplish a certain amount of drying, a high content of moisture in the external air should be assumed.

The air leaving the drying-room also is almost never completely saturated. Although this desirable condition is seldom attained, yet in this section the quantities of air and heat will be first calculated on the assumption of complete saturation. Other degrees of saturation will be considered subsequently.

Fig. 1 represents diagrammatically the arrangement of a simple air-drying apparatus.

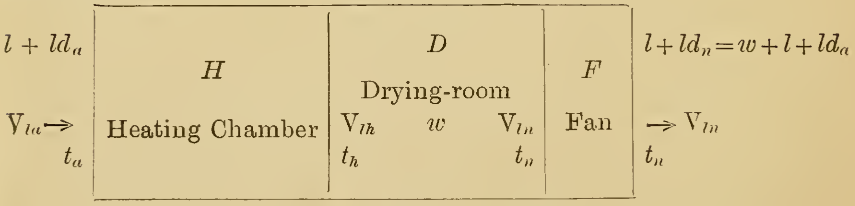


Fig. 1.

The external air, l, which contains d_a kilos. of water vapour, in 1 kilo., enters the heating chamber at the temperature t_a and leaves it at the higher temperature t_h. In its passage through the drying-room, *D*, the air takes up the weight of water w, and is thereby cooled to the temperature t_n. A fan, *F*, is generally used to drive the warm air now laden with the moisture, $ld_n = w + ld_a$, into the atmosphere.

From what has preceded it may be seen that the air to be used in drying must fulfil two conditions:—

1. The quantity of heat which the weight of air, l, and its moisture, ld_a, can give out in the drying-room in cooling from the temperature of entry, t_h, to that of exit, t_n, must be sufficient to heat the material from its original temperature t_u to the temperature t_z, *and* to evaporate the weight of water w.

2. The air must be in such a condition that, at its exit temperature t_n, it can retain in the form of vapour the weight of water w and *also* the water vapour ld_a, which it brought from the atmosphere.

If we denote by r the specific heat of air $= 0{\cdot}2375$, by s the specific heat of water vapour $= 0{\cdot}475$, and by C_n the amount of heat in calories which is utilised in the drying-room, we obtain from the above conditions the equations—

$$(lr + ld_a s)\,(t_h - t_n) = C_n. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$l\,(d_n - d_a) = w \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

the latter of which may be written—

$$l = \frac{w}{d_n - d_a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

When this is inserted in equation (5) we obtain—

$$\frac{w}{d_n - d_a}(r + d_a s)\,(t_h - t_n) = C_n \quad . \quad . \quad . \quad . \quad . \quad (8)$$

or, since $r = 0{\cdot}2375$ and $s = 0{\cdot}475$—

$$\frac{t_h - t_n}{d_n - d_a} = \frac{C_n}{w\,(0{\cdot}2375 + d_a\,0{\cdot}475)} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

In this equation (9) the following are known in each case:—

w = weight of water to be evaporated in the unit of time.
t_h = the highest temperature of the air in the hot room, which is to be made as high as the drying material will bear.
t_a = the temperature of the external air which is used.
C_n = the quantity of heat, in calories, to be given out by the air in the drying-room. It is the sum of the quantities of heat required to heat up the material to the temperature t_z, and to evaporate the weight of water, w, out of this material.

The proportion of solid matter in the material to be dried may be great or small. In what follows we shall neglect entirely the quantity of heat required to warm the solid matter (or, more accurately, whatever remains after drying) of the drying material, since it is different in every case, is always a small proportion of the total expenditure of heat, and may be disregarded in view of the factors of safety required in practice. Thus it will be assumed that only the water to be evaporated has to be heated from its original temperature, t_u (in the tables t_u is always taken as 15° C.) to the temperature, t_n, of the air exit, for which purpose $w\,(t_n - t_u)$ calories are required.

For the evaporation of 1 kilo. of water at the temperature t_n, $640 - t_n$ calories are required, this being the *Latent Heat.*

The quantity of heat, C_n, necessary to evaporate the water (the useful work of the drying apparatus) is therefore—

$$C_n = w\,(t_n - t_u) + w\,(640 - t_n),$$

or

$$C_n = w\,(640 - t\ ) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (10)$$

The *unknown* quantities in equation (9) are t_n and d_n, the outlet temperature and the proportion of water in the air leaving the apparatus.

When the air at its exit is supposed to be saturated with water vapour (for which condition alone Tables I. and II.

hold good), the quantities t_n and d_n are mutually dependent, since to each temperature, t_n, there corresponds a quantity of water, d_n, to be found from Table I.

In order now to find the unknown quantities t_n and d_n of equation (9) the values of the known quantities must be inserted, and then the values of t_n and d_n found by trial, *i.e.*, an arbitrary value of t_n is chosen, the corresponding value of d_n taken from Table I., both values inserted in the equation, and the operation repeated until the two sides of the formula balance.

If in this manner the temperature of exit, t_n, and consequently the water content of the air, d_n, be fixed, then the weight of air, l (columns 2 and 3, Table II.), required to evaporate the weight of water, w, can be found by means of equation (7).

The absolute weight of the moisture which this calculated weight of air, l, brings from the exterior into the apparatus is obtained (Table II., pp. 22-25, column 4) by multiplying l by the factor d_a (Table I., pp. 11-12, columns 10, 11, 12, 15, 18 and 21).

The total quantity of heat, C_g, required to heat the weight of air, l, and the moisture it contains, from their initial temperature, t_a, to the highest temperature, t_h, is obtained from the formula—

$$C_g = l\,(0{\cdot}2375 + d_a\,0{\cdot}475)\,(t_h - t_a) \quad . \quad . \quad . \quad . \quad (11)$$

The larger C_g is in proportion to C_n the less economical is the work of the drying apparatus (Table II., pp. 22-25, column 8).

Finally, it is required to find the volumes of the air at its different temperatures.

The weight of air which enters the drying-room is the same as that which comes out. We suppose that this air is saturated with moisture at each period, *i.e.*, at the temperature of the atmosphere, t_a, and at the outlet temperature t_n. The pressure of the air in the two cases is different; but it is known, since it is the difference between the atmospheric pressure and the pressure of the saturated vapour in the air.

Thus in order to find the volumes, V_{la} and V_{ln}, of the weight of air, l, the weight of 1 cubic metre of dry air at the same temperature and pressure (atmospheric pressure *minus* vapour pressure) is divided into the calculated weight of air, l, *i.e.*, the calculated weight of air, l, is divided by the weights given in Table I., columns 7, 8, 9, 14, 17 and 20, for the particular temperatures of exterior and exit. Thus the columns 5 and 7 of Table II. are obtained—

$$V_{la} = \frac{l}{k_l}. \qquad V_{ln} = \frac{l}{k_l}.$$

In order to find the volume of the heated air, in the condition in which it leaves the heating chamber, a somewhat different process must be adopted. In this heated air the water vapour is no longer saturated, and is therefore subject to different laws. At high temperatures superheated vapour has a lower pressure (*i.e.*, that of the "permanent" gases) than saturated vapour. But in the neighbourhood of its point of condensation (and this is the region which comes into consideration here) the laws followed by slightly superheated vapour are not accurately known. With the hope that no considerable error is being introduced, we shall assume for the purposes of calculation that the vapour, although little superheated, behaves as a so-called permanent gas.

The vapour is diffused through the air. In regard to weight, pressure and total volume nothing will be altered if we suppose this interdiffusion of air and vapour suddenly to cease. We should then see air and vapour existing with unaltered pressure in two adjoining spaces separated by a membrane; the two spaces together would have the same volume as the space originally occupied by the mixture of air and vapour. If the mixture was previously at a pressure of 760 mm., the same would be the case after the separation. Thus, in order to find the volume of the mixture of air and vapour, it is only necessary to add the volumes of the two portions.

There is no difficulty in finding the volume of a certain weight of dry air or of vapour above its point of saturation, at a given temperature and pressure, if the following formulæ, which express Mariotte's law, be used:—

$$\frac{V_l\, p}{273 + t} = R, \quad \text{or} \quad \frac{V_d\, p}{273 + t} = R \quad . \quad . \quad . \quad (12)$$

R is a constant for each gas: for air R = 29·27, and, according to G. Schmidt, for superheated vapour R = 46·83.

Accordingly the formula for calculating the volume of the hot air and of the vapour mixed with it, at the temperature t_h is—

$$V_g = V_{lh} + V_{dh} = l \left\{ \frac{273 + t_h}{p} (29{\cdot}27 + 46{\cdot}83\, d_a) \right\} \quad . \quad (13)$$

Column 6 of Table II. is calculated by this method.

In order to make clear the manner in which the considerations developed up to this point may be utilised in special cases in practice, an example will be at once calculated; at the same time it shows how the figures in Table II. (pp. 22-25) are obtained.

Example. One hundred kilos. of water are to be evaporated by means of air, the maximum temperature of which may not exceed $t_h = 100°$ C., it being assumed that the atmospheric air and the air leaving the apparatus are both completely saturated with vapour and that the barometric height is 760 mm.

The atmospheric air may have any ordinary temperature. Thus it will be necessary to calculate the required values for all possible external temperatures. Since, however, the calculations are repeated for each external temperature, we shall here complete them for the external temperature of 20° C. alone.

The following quantities are to be determined: The requisite weight of air, l, temperature of the exit of the air, t_n, the volume of the air before entry, V_{la}, after heating to 100° C., V_{lh}, at exit, V_{ln}, and the quantity of heat to be expended, C_g.

Equation (9) is—

$$\frac{t_h - t_n}{d_n - d_a} = \frac{C_n}{w\,(0{\cdot}2375 + d_a\,0{\cdot}475)}.$$

Now the highest temperature of the air, $t_h = 100°$, the external temperature, $t_a = 20°$, and hence 1 kilo. of air contains the weight of water, $d_a = 0{\cdot}0148$ kilo. (Table I., column 11); the weight of water to be evaporated, $w = 100$ kilos. The material to be dried and the water it contains are at the temperature $t_u = 15°$, hence the heat necessary for evaporation—

$$C_n = (640 - 15)\,100 = 62{,}500 \text{ calories.}$$

If these values be inserted in equation (9), we obtain—

$$\frac{100 - t_n}{d_n - 0{\cdot}0148} = \frac{62500}{100\,(0{\cdot}2375 + 0{\cdot}0148 \times 0{\cdot}475)}$$

or,

$$\frac{100 - t_u}{d_n - 0{\cdot}0148} = 2556{\cdot}2.$$

The quantities t_n (temperature of exit) and d_n (the weight of water in 1 kilo. of air at that temperature) depend directly on one another in such a manner that the maximum amount of water in air at any definite temperature is known; but these quantities are not proportional to one another. It is therefore necessary to insert, by trial, different values for t_n and the corresponding values for d_n obtained from Table I., column 11, until the two sides of the equation balance.

After several trials it will be found that for $t_n = 36{\cdot}25$ and the corresponding $d_n = 0{\cdot}0398$ (Table I., column 11, by interpolation)—

$$\frac{100 - 36{\cdot}25}{0{\cdot}0398 - 0{\cdot}0148} = 2550,$$

which is sufficiently near to the number 2556·2. Thus the *outlet temperature* from the drying apparatus is 36·25° C.

The *weight of air*, l, is obtained from equation (7)—

$$l = \frac{w}{d_n - d_a} = \frac{100}{0{\cdot}0398 - 0{\cdot}0148} = 4{,}000 \text{ kilos.}$$

The *weight of moisture*, ld_a, which was originally in the 4,000 kilos. of atmospheric air, is obtained by multiplying the weight of air by the number which represents the weight of saturated water vapour contained in 1 kilo. of air at 20° C., this is $d_a = 0{\cdot}0148$ (Table I., column 11). Thus, in the 4,000 kilos. of air there were originally—

$$ld_a = 4000 \times 0{\cdot}0148 = 59{\cdot}2 \text{ kilos. of water vapour.}$$

The *volumes of the air*, V_{la} and V_{ln}, in cubic metres, before its entry and at its exit, are obtained by division of the requisite weight of air, l, by the weight of 1 cubic metre of *dry* air at the particular temperatures 20° and 36·25° C. (Table I., column 8)—

At 20° C. $$V_{la} = \frac{4000}{1{\cdot}1771} = 3{,}389 \text{ cubic metres.}$$

At 36·25° C. $$V_{ln} = \frac{4000}{1{\cdot}075} = 3{,}721 \text{ cubic metres.}$$

The *volume of the heated air*, V_{lh}, is obtained from equation (13)—

$$V_{lh} = l\left\{\frac{273 + t_h}{p}(29{\cdot}27 + 46{\cdot}83\, d_a)\right\},$$

in which must be replaced—

$p = 10{,}336$ kilos., $t_h = 100°$ C., $l = 4{,}000$ kilos., $ld_a = 59{\cdot}2$ kilos.

Therefore—

$$V_{lh} = \frac{273+100}{10336}(29{\cdot}27 \times 4000 + 59{\cdot}2 \times 46{\cdot}83) = 4{,}323 \text{ cubic metres.}$$

Finally, the quantity of heat, C_g, is to be calculated, which is required to heat 4,000 kilos. of air and 59·2 kilos. of water vapour from 20° C. to 100° C. It is obtained from equation (11)—

$$C_g = (0{\cdot}2375\, l + ld_a\, 0{\cdot}475)(t_h - t_a),$$

in which

$l = 4000$, $ld_a = 59{\cdot}2$, $t_h = 100°$ C., $t_a = 20°$ C.

Therefore—

$$C_g = (4000 \times 0{\cdot}2375 + 59{\cdot}2 \times 0{\cdot}475)(100 - 20) = 78{,}260 \text{ calories.}$$

The figures in Table II. have been calculated in this manner.

Generally speaking, in order to estimate the dimensions of an installation for a definite purpose the limiting conditions will alone be used, in which the air to be employed is either at the lowest or the highest temperature; occasionally, however, intermediate values will be more suitable. Accordingly, in Table II. (pp. 22-25), account has been taken of certain cases falling between the limits, which latter alone will be considered later on. The limits of the temperature of the air may be taken as − 20° and + 30° C.

TABLE II.

Weight and Volume of Air, Outlet Temperature of Air and Expenditure of Heat required to evaporate 100 kilos. of water, when the external temperature, t_a, = – 20° C. to + 30° C., the maximum temperature, t_h, = 30° C. to 130° C., the barometric pressure, q, = 760 mm. The external air and the air at its exit are both *completely* saturated with water vapour.

1	2	3	4	5	6	7	8
Temperature of the External Air, t_a.	Outlet Temperature of the Air, t_n,	Weight of dry Air, l.	Weight of the Moisture in the Air, ld_a.	Volume of the Air.			Heat Expended in Warming the Air, C_g.
				At Entry, V_{la}.	After Heating, V_{lh}.	At Exit, V_{ln}.	
° C.	° C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.
Maximum Temperature, t_h = 30° C.							
– 20	11·0	13,230	10·09	9,520	11,360	10,780	157,347
– 15	11·5	13,550	15·58	9,900	11,641	11,070	145,147
– 10	12·0	14,000	24·08	10,450	11,940	11,470	133,480
– 5	12·75	14,560	36·98	11,048	12,495	11,960	121,660
0	13·5	16,666	64·49	12,650	14,380	13,735	119,640
5	15·5	17,640	97·54	14,050	15,262	14,630	105,625
10	17·25	20,500	158·26	16,645	17,797	17,010	98,880
15	19·75	26,200	282·96	21,850	22,857	22,230	95,340
20	22·75	38,000	665·0	32,285	33,833	32,771	93,000
25	26·0	66,666	1346·65	58,250	59,010	58,530	87,357
30							
Maximum Temperature, t_h = 35° C.							
– 20	12·75	11,800	9·00	8,495	10,295	9,694	154,363
– 15	13·0	11,830	13·60	8,670	10,318	9,730	140,800
– 10	13·5	12,222	21·02	9,134	10,770	10,076	131,085
– 5	14·25	12,900	32·94	9,850	11,356	10,725	120,000
0	15·5	13,100	50·69	10,000	11,458	10,890	109,725
5	17·0	14,550	80·46	11,580	12,792	12,188	104,820
10	19·0	15,920	123·00	12,900	13,858	13,460	96,225
15	21·0	19,230	207·68	16,000	17,063	16,430	93,300
20	24·0	23,260	346·25	19,250	20,670	20,230	85,335
25	27·0	33,333	673·33	29,107	30,013	29,500	82,350
30	30·0	66,666	1833·32	59,690	60,706	60,000	82,000

1	2	3	4	5	6	7	8
Temperature of the External Air, t_a.	Outlet Temperature of the Air, t_n.	Weight of Dry Air, l.	Weight of the Moisture in the Air, ld_a.	Volume of the Air. At Entry, V_{la}.	Volume of the Air. After Heating, V_{lh}.	Volume of the Air. At Exit, V_{ln}.	Heat Expended in Warming the Air C_g.
° C.	° C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.
Maximum Temperature, t_h = 40° C.							
– 20	15·0	10,000	7·63	7,200	8,790	8,290	142,716
– 15	15·25	10,150	11·67	7,435	8,928	8,440	132,880
– 10	15·5	10,550	18·14	7,865	9,350	8,773	125,710
– 5	16·25	10,800	27·43	8,250	9,586	9,015	115,997
0	17·0	11,710	45·32	9,125	10,415	9,881	112,120
5	18·75	12,090	66·86	9,625	10,781	10,335	101,258
10	20·75	13,020	100·51	10,530	11,650	11,100	94,200
15	22·75	15,000	162·0	12,500	13,488	12,935	90,975
20	25·25	17,070	252·64	14,130	15,445	14,910	85,000
25	28·25	21,700	438·34	18,901	19,801	19,660	82,445
30	31·75	32,260	887·25	28,890	29,770	29,170	80,818
Maximum Temperature, t_h = 50° C.							
– 20	17·5	8,250	6·33	6,000	7,582	6,950	138,180
– 15	18·0	8,300	9·54	6,080	7,592	7,118	128,505
– 10	18·5	8,400	14·45	6,278	7,692	7,175	120,120
– 5	19·5	8,630	21·92	6,550	7,912	7,350	113,300
0	20·5	8,800	34·06	6,670	8,085	7,500	105,300
5	22·0	9,000	49·77	7,165	8,292	7,610	97,245
10	23·0	9,600	79·72	7,758	8,830	8,446	92,160
15	25·0	10,640	114·91	8,866	9,906	9,306	90,370
20	27·0	11,760	174·05	9,809	10,993	10,370	84,250
25	30·0	13,700	276·74	11,970	12,845	12,267	80,625
30	33·5	15,700	431·75	14,058	14,968	14,410	78,874
Maximum Temperature, t_h = 60° C.							
– 20	21·0	6,600	5·03	4,758	6,221	5,637	125,600
– 10	21·5	6,800	11·69	5,082	6,427	5,840	113,470
0	23·0	7,000	27·09	5,310	6,638	6,185	100,500
10	25·75	7,310	56·43	5,935	6,974	6,400	88,145
20	29·5	8,370	123·87	6,925	8,075	7,475	83,248
30	35·25	10,310	283·53	9,232	10,143	9,520	77,490

1	2	3	4	5	6	7	8
				Volume of the Air.			
Temperature of the External Air, t_a.	Outlet Temperature of Air at Exit, t_n.	Weight of Dry Air, l.	Weight of the Moisture in the Air, ld_a.	At Entry, V_{la}.	After Heating V_{lh}.	At Exit, V_{ln}.	Heat Expended in Warming the Air, C_g.
° C.	° C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.
Maximum Temperature, t_h = 70° C.							
- 20	24·0	5,430	4·14	3,950	5,266	4,720	116,242
- 10	24·5	5,555	9·54	4,155	5,396	4,840	105,920
0	26·0	5,610	21·71	4,265	5,468	5,000	94,010
10	28·0	5,950	46·03	4,835	5,836	5,380	86,040
20	31·5	6,930	103·30	5,775	6,922	6,305	82,700
30	37·5	8,200	225·50	7,342	8,294	7,695	77,200
Maximum Temperature, t_h = 80° C.							
- 20	26·0	4,845	3·70	3,485	4,910	4,240	115,250
- 10	26·5	4,848	8·34	3,623	4,920	4,270	103,950
0	28·0	4,850	18·77	3,675	4,939	4,390	92,880
10	30·0	5,070	39·14	4,119	5,122	4,540	85,610
20	33·0	5,555	82·21	4,600	5,675	5,180	81,498
30	38·0	6,100	167·75	5,461	6,356	5,915	76,400
Maximum Temperature, t_h = 90° C.							
- 20	28·0	4,125	3·15	2,893	4,243	3,657	107,910
- 10	28·75	4,155	7·15	3,106	4,260	3,670	99,010
0	30·0	4,235	16·39	3,215	4,377	3,792	91,170
10	31·75	4,370	33·74	3,550	4,544	3,954	84,320
20	34·5	4,750	70·30	3,925	5,195	4,366	81,340
30	39·5	4,950	136·13	4,432	3,308	4,710	75,400
Maximum Temperature, t_h = 100° C.							
- 20	30·5	3,610	2·75	2,532	3,820	3,245	103,080
- 10	31·0	3,630	6·24	2,710	3,875	3,275	95,150
0	32·0	3,670	14·20	2,780	3,901	3,267	87,900
10	34·0	3,740	28·87	3,035	4,000	3,430	81,180
20	36·25	4,000	59·20	3,389	4,323	3,721	78,860
30	41·0	4,050	111·38	3,626	4,503	3,840	74,980

1	2	3	4	5	6	7	8
Temperature of the External Air, t_a. ° C.	Outlet Temperature of Air at Exit, t_n. ° C.	Weight of Dry Air, l. Kilos.	Weight of the Moisture in the Air, ld_a. Kilos.	Volume of the Air.			Heat Expended in Warming the Air, C_g. Calories.
				At Entry, V_{la}. Cubic Metres.	After Heating, V_{lh}. Cubic Metres.	At Exit, V_{ln}. Cubic Metres.	
Maximum Temperature, t_h = 110° C.							
– 20	32·0	3,290	2·51	2,375	3,615	2,980	101,790
– 10	32·5	3,300	5·68	2,465	3,621	3,000	95,040
0	33·5	3,333	12·89	2,529	3,680	3,101	87,780
10	35·0	3,460	26·71	2,809	3,845	3,195	83,400
20	37·5	3,560	52·69	2,947	4,003	3,341	78,300
30	41·75	3,690	101·48	3,304	4,228	3,575	74,000
Maximum Temperature, t_h = 120° C.							
– 20	33·6	2,980	2·27	2,089	3,318	2,722	100,632
– 10	34·0	3,000	5·16	2,245	3,346	2,750	92,950
0	35·0	3,015	11·67	2,285	3,374	2,795	86,640
10	36·5	3,080	23·78	2,505	3,450	2,870	81,730
20	39·0	3,150	46·62	2,607	3,587	3,031	77,000
30	42·75	3,230	88·83	2,892	3,751	3,150	72,810
Maximum Temperature, t_h = 130° C.							
– 20	35·5	2,700	2·06	1,895	3,086	2,495	96,300
– 10	36·0	2,720	4·68	2,033	3,113	2,432	90,720
0	36·5	2,753	10·65	2,088	3,162	2,565	85,540
10	37·75	2,800	21·63	2,274	3,262	2,630	81,000
20	40·25	2,860	42·33	2,365	3,342	2,730	77,000
30	43·75	2,895	79·61	2,592	3,451	2,845	72,600

Several conclusions may be drawn from an examination of Table II. :—

In the first place, it is evident that the consumption of heat in drying by means of air decreases rapidly when the temperature, t_h, to which the air is previously heated, is raised. When the air is slightly heated the expenditure of heat, C_g, in drying 100 kilos. of water is very large, in fact two to three times as great as the theoretical quantity of heat, C_n, required to evaporate the water.

Next, we find that the quantity of heat required increases considerably when the external temperature is diminished. The colder the atmosphere, the more heat is necessary to evaporate 100 kilos. of water.

Further, it appears that the weight of air to be conveyed into the drying-room increases as its temperature increases. The lower is the outside temperature the less air is required, the maximum temperature in the drying apparatus remaining the same and also supposing that the atmospheric air is always saturated with moisture. But the smaller quantity of colder-air requires many more calories than the larger quantity of warmer air in order to be raised to the same temperature, t_h

Hence we obtain the rules :—

1. *The hot air, before entry into the drying-room, should be given the highest temperature compatible with the nature of the material to be dried.*

2. *The heating surface must be so large that it suffices even on the coldest days.*

3. *The apparatus for circulating the current of air should be of sufficient size to convey the great quantity of air required on the hottest days.*

Thus on cold days, if the heating surface be sufficient, the blowing apparatus will be too large. The latter may then be run below its full capacity. On warm days the blowing apparatus is sufficient and the heating surface too large. A portion of the latter should alone be used.

The weight of air required in unit time has a very variable volume. The volume is smallest before entry (Table II., column 5), largest after heating (column 6), and intermediate when it leaves the drying-room (column 7). In order that the air may not have an excessive velocity in any part of the apparatus, the flues and transverse sections of the apparatus, across which the air passes, should be given dimensions in accordance with the varying volumes. When the air is moved mechanically it is always more convenient to move a smaller volume. Thus it seems desirable to arrange the fan before the heating chamber. If this is not convenient it should be placed at the exit from the apparatus. The most unfavourable position would be after the heating chamber.

Fans cause a slight vacuum in the inlet current of air and a slight pressure in the outlet air. Subsequently it will be shown that it is favourable to the output of the apparatus and the expenditure of heat if there is a lower pressure in the drying-room than in the outside atmosphere; thus it is advisable to place the fan at the exit from the drying-room, *i.e.*, it is better to withdraw the air from the drying-room than to pump it in.

At sea-level the barometer probably varies between 740 and 780 mm. Table II. is calculated only for the barometric height of 760 mm., because even such large and rare variations as 20 mm. of mercury have a very small influence on the weight and volume of the required air, so that this influence would hardly be perceptible in the figures in the table. However small the influence may be, it is however in favour of the higher pressure, *i.e.*, the higher the barometer the less air is required and the more cheaply is the drying accomplished, other conditions being the same. The lower the barometer the more air and heat are required to evaporate a certain weight of water. In any case the advantage or disadvantage due to this cause is very slight.

What has just been said holds good only for the case in which the pressure in the drying-room is equal to that of the atmosphere; only when the heights of the barometer in the drying-room and outside are the same is high pressure an advantage. The opposite is the case when another pressure, higher or lower than that of the atmosphere, is artificially produced in the drying-room; then a lower pressure is advantageous, as will be seen in Chapter IV.

B.—*When the atmospheric air is* completely *saturated before entry, but at its exit is only* $\frac{3}{4}$, $\frac{1}{2}$ *or* $\frac{1}{4}$ *saturated with moisture.*—Tables III., IV., V. and VI.

For the calculation of Tables II. (pp. 22-25) and III. (pp. 30-31) it was assumed that the atmospheric air introduced into the apparatus and also the air leaving it were completely saturated with water vapour. The figures in the tables are correct only when this is the case.

Complete saturation of the air at entry or exit practically never occurs. Neither is the atmospheric air quite saturated with water vapour, nor can a drying apparatus be constructed so that the air shall leave it in that condition.

We shall now consider the case in which the air enters the apparatus completely saturated, but leaves it in a state of incomplete saturation.

Air is saturated when unit volume of it contains the same weight of water as the same space could contain if air were absent. Air is saturated to the extent of $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ when unit volume contains $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ of the weight of water which it can contain at the maximum.

As the degree of saturation of the air deceases, so also does the pressure of the water vapour in the air, and since the barometric pressure is the sum of the pressures of air and vapour, unit volume contains a greater weight of air, the smaller the weight of water it contains.

In order to have the necessary figures at hand for the succeeding calculations, Table III. (pp. 30-31) has been drawn up. In it are given the pressures of water vapour and air and the weights of 1 cubic metre of each at the degrees of saturation represented by $\frac{3}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$. These figures are given for the barometric height of 760 mm. alone, since differences in the barometric pressure do not give rise to any considerable variations in the figures.

In the columns 2, 7 and 12 of Table III. are given the weights of 1 cubic metre of water vapour, $\frac{3}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$ saturated, at temperatures from − 20° to + 100° C. They are found by taking the corresponding fraction of the weight of 1 cubic metre of vapour as given in Table I., column 3, *e.g.*, at − 20° C. One cubic metre of saturated water vapour weighs 0·00106 kilo., therefore 1 cubic metre, which contains half the quantity of saturated vapour at this temperature, contains $\frac{0 \cdot 00106}{2} = 0 \cdot 00053$ kilo. (column 7).

In columns 3, 8 and 13 are given the pressures of this vapour. The partially saturated vapour is to be regarded as superheated, and, consequently, formula (12)—

$$\frac{V^d p_l}{273 + t} = R,$$

in which R = 46·83, is to be applied.

The weight of 1 cubic metre of vapour is given by—

$$k_d = \frac{1}{V_d}, \qquad \text{and} \qquad V_d = \frac{1}{k_d}$$

The pressure p_l, in kilos. per square metre at the absolute pressure q_d measured in millimetres of mercury, is given by—

$$p_l = \frac{p\,q_d}{760} = \frac{10{,}336\,q_d}{760},$$

since p, the pressure of the atmosphere, is 10,336 kilos. per square metre.

Thus equation (12) takes the form—

$$R = \frac{\frac{1}{k_d}\ \frac{10{,}336\,q_d}{760}}{273 + t}.$$

TABLE

Pressures and Weights of 1 cubic metre of ¾, ½ and ¼
The Weights of ¾, ½ and ¼ Saturated Vapour contained in

from − 20°

1	2	3	4	5	6	7	8
	The Air is ¾ Saturated with Water Vapour.					The Air is ½ Satu	
Temperature. °C	Weight of the Vapour in 1 Cubic Metre. Kilos.	Pressure of the Vapour, q_d. Mm.	Pressure of the Air, q_l. Mm.	Weight of Dry Air in 1 Cubic Metre. Kilos.	Weight of Vapour, *d*, in 1 Kilo. of Air. Kilos.	Weight of the Vapour in 1 Cubic Metre. Kilos.	Pressure of the Vapour, q_d. Mm.
− 20	0·00080	0·697	759·3	1·390	0·000575	0·00053	0·461
− 15	0·00122	1·080	759·0	1·366	0·00090	0·00078	0·720
− 10	0·00175	1·325	758·7	1·339	0·00130	0·00115	0·816
− 5	0·00252	2·320	757·7	1·317	0·00192	0·00168	1·540
0	0·00372	3·444	756·6	1·286	0·00288	0·00288	2·254
5	0·00522	4·999	755·0	1·261	0·00414	0·00348	3·32
10	0·00713	6·886	753·1	1·235	0·00577	0·00475	4·55
15	0·00974	9·54	750·5	1·208	0·00806	0·00640	6·36
20	0·01317	13·2	746·8	1·194	0·01103	0·00877	8·84
25	0·01736	17·8	752·2	1·169	0·01485	0·01156	11·8
30	0·0231	24·1	735·9	1·128	0·0205	0·0154	16·1
35	0·0298	31·0	729·0	1·101	0·0270	0·0199	20·6
40	0·0384	41·3	718·7	1·067	0·0351	0·0256	27·54
45	0·0492	53·1	707·0	1·032	0·0476	0·0328	35·4
50	0·0626	69·2	691·0	0·994	0·0625	0·0417	46·3
55	0·0723	81·6	679·0	0·951	0·076	0·0522	54·4
60	0·0984	112·8	647·2	0·899	0·109	0·0656	75·0
65	0·1217	141·5	618·5	0·850	0·143	0·0811	94·3
70	0·1494	175·6	584·4	0·789	0·189	0·0996	117·7
75	0·1830	218·9	541·1	0·722	0·253	0·1220	145·9
80	0·2109	255·1	505·0	0·665	0·317	0·1479	180·0
85	0·2681	330·0	420·0	0·546	0·491	0·1787	220·0
90	0·3210	401·1	359·0	0·458	0·700	0·214	267·4
95	0·3830	485·0	275·0	0·347	1·104	0·255	323·4
100	0·4845	619·0	141·0	0·176	2·750	0·303	412·6

III.

Saturated Water Vapour and of the accompanying Dry Air.

1 kilo. of Air, with the barometer at 760 mm., and at temperatures to + 100° C.

9	10	11	12	13	14	15	16
rated with Water Vapour.			The Air is ½ Saturated with Water Vapour.				
Pressure of the Air, q_l.	Weight of Dry Air in 1 Cubic Metre.	Weight of Vapour, *d*, in 1 Kilo. of Air.	Weight of the Vapour in 1 Cubic Metre.	Pressure of the Vapour, q_d.	Pressure of the Air, q_l.	Weight of Dry Air in 1 Cubic Metre.	Weight of Vapour, *d*, in 1 Kilo. of Air.
Mm.	Kilos.	Kilos.	Kilos.	Mm.	Mm.	Kilos.	Kilos.
759·5	1·395	0·00038	0·00027	0·235	759·8	1·390	0·00020
759·3	1·367	0·00057	0·00044	0·360	759·7	1·367	0·00032
759·2	1·340	0·00086	0·00060	0·408	759·6	1·341	0·000447
758·5	1·319	0·00127	0·00084	0·770	759·2	1·320	0·000636
757·75	1·288	0·00220	0·00124	1·164	758·8	1·290	0·00100
756·7	1·264	0·00275	0·00174	1·660	758·3	1·267	0·00136
755·4	1·238	0·00384	0·00238	2·275	757·7	1·237	0·00192
753·7	1·213	0·00530	0·00325	3·180	756·8	1·218	0·00257
751·2	1·190	0·00737	0·0044	4·440	755·5	1·197	0·00369
748·2	1·154	0·01000	0·0058	5·930	754·0	1·172	0·00500
744·0	1·141	0·0135	0·0077	8·03	752·0	1·153	0·00668
739·4	1·116	0·0170	0·0099	10·30	749·7	1·132	0·00874
732·5	1·087	0·0235	0·0128	13·772	746·2	1·107	0·0115
724·6	1·057	0·0310	0·0164	17·70	742·3	1·084	0·0151
713·7	1·026	0·0406	0·0209	23·0	737·0	1·060	0·0197
705·6	0·996	0·0530	0·0261	27·2	733·0	1·045	0·0250
685·0	0·952	0·0689	0·0328	37·5	722·5	1·004	0·0300
665·7	0·915	0·0886	0·0406	47·17	712·8	0·980	0·0470
642·3	0·867	0·1149	0·0496	58·9	701·1	0·946	0·0524
614·1	0·820	0·1485	0·061	72·9	687·0	0·917	0·0665
580·0	0·763	0·1938	0·073	90·0	670·0	0·882	0·0827
540·0	0·702	0·2540	0·0894	110·0	650·0	0·845	0·106
492·6	0·628	0·3407	0·107	133·7	626·3	0·799	0·134
436·6	0·551	0·4630	0·128	161·7	598·3	0·755	0·169
347·4	0·433	0·7000	0·1515	206·3	553·7	0·689	0·220

The pressure of unsaturated vapour in the air is therefore—

$$q_d = \frac{R\ (273 + t)\ k_d\ 760}{10{,}336}$$

Columns 3, 8 and 13 of Table III. are calculated by means of this equation.

Example.—At a temperature of − 20° C. and at a saturation of 50 per cent. (= $\frac{1}{2}$) the pressure of aqueous vapour in millimetres of mercury is—.

$$q_d = \frac{46{\cdot}83\ (273 - 20)\ 0{\cdot}00053 \times 760}{10{,}336} = 0{\cdot}461 \text{ mm.}$$

The columns 4, 9 and 14, in which the pressure of the air is given, are obtained by taking the difference between the atmospheric pressure of 760 mm. and the pressure of the vapour q_d.

Example.—In the last example the tension of the air is—

$$q_l = 760 - 0{\cdot}461 = 759{\cdot}539 \text{ mm.}$$

In columns 5, 10 and 15 is given the weight of the dry air contained in 1 cubic metre, which also contains $\frac{3}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$ saturated vapour. This weight is determined according to equation (3)—

$$k_l = \frac{0{\cdot}0001252}{1 + et} \frac{pq_l}{760}.$$

Inserting the values for p and e, we obtain—

$$k_l = \frac{0{\cdot}0001252 \times 10{,}336\ q_l}{(1 + 0{\cdot}003665\ t)\ 760}.$$

Example.—In the above example for $t_n = -20°$ C. and semi-saturation, $q_l = 759{\cdot}539$, hence the weight of air in 1 cubic metre is—

$$k_l = \frac{0{\cdot}0001252 \times 10{,}336 \times 759{\cdot}539}{\{1 + 0{\cdot}003665\ (-20)\}\ 760} = 1{\cdot}395 \text{ kilos.}$$

Finally, columns 6, 11 and 16 give the weight of vapour contained in 1 kilo. of air. This is obtained by division of the weight of air (column 10) into the weight of vapour (column 7).

Example.—For $t = -20°$ C. and semi-saturation—

$$d = \frac{k_d}{k_l} = \frac{0{\cdot}00053}{1{\cdot}395} = 0{\cdot}00038 \text{ kilo.}$$

In this manner Table III. has been compiled.

With the aid of Table III., Tables IV. (p. 35), V. (p. 36), and VI. (p. 37), can now be calculated. They deal with the cases in which the external air is completely saturated, but the air leaving the apparatus is only $\frac{3}{4}$ (IV.), $\frac{1}{2}$ (V.) and $\frac{1}{4}$ (VI.) saturated. These tables give the weights and volumes of air necessary to dry 100 kilos. of water, the outlet temperature of the air and the consumption of heat, just as Table II. (pp. 22-25) gives the corresponding values for saturated emergent air.

The calculations are performed quite in a similar manner to those in section A of this chapter, but for the sake of greater clearness an example will be given.

Example.—With the barometer at 760 mm., $w = 100$ kilos. of water are to be evaporated by means of air, which may be heated to the maximum temperature $t_h = 100°$ C.; the external temperature, $t_a = 0°$ C. It is assumed that the external air is completely saturated with water vapour and that the air leaving the apparatus is $\frac{3}{4}$ saturated. The temperature of the material to be dried is $t_n = 15°$ C.

According to equation (9)—

$$\frac{t_h - t_n}{d_n - d_a} = \frac{C_n}{w\,(0{\cdot}2375 + 0{\cdot}475\,d_a)},$$

now $t_h = 100°$, $w = 100$ kilos., $C_n = 62{,}500$, $d_a = 0{\cdot}00387$ (Table I., column 11), hence

$$\frac{100 - t_n}{d_n - 0{\cdot}00387} = \frac{62{,}500}{100\,(0{\cdot}2375 + 0{\cdot}00387 \times 0{\cdot}475)} = 2616.$$

By trial insertions of various values for t_n and the corresponding values for d_n from Table III. (pp. 30-31) column 6, it is finally found that $t_n = 36°$ and $d_n = 0{\cdot}0284$ make the left-hand side of the equation equal to 2610. Thus the outlet *temperature* is 36° C.

The requisite *weight of air*, l, is obtained from equation (7)—

$$l = \frac{100}{d_n - 0{\cdot}00387} = \frac{100}{0{\cdot}0284 - 0{\cdot}00387} = 4{,}076 \text{ kilos.}$$

The *saturated water vapour* originally contained in 4,076 kilos. of air is $ld_a = 4076 \times 0{\cdot}00387 = 15{\cdot}774$ kilos.

The *volume* V_{la}, of the 4,076 kilos. of air at $t_a = 0°$ C. is, according to Table I., column 8—

$$V_{la} = \frac{4{,}076}{1{\cdot}2832} = 3{,}176 \text{ cubic metres.}$$

The *volume*, V_{lh}, of the air after heating to 100° C. is obtained from equation (13), in which we insert—

$$t_h = 100°, \qquad l = 4{,}076, \qquad ld_a = 15{\cdot}8.$$

Therefore—

$$V_{lh} = \frac{273 + 100}{10{,}336}(29{\cdot}27 \times 4076 + 46{\cdot}83 \times 15{\cdot}8) = 4333{\cdot}6 \text{ cubic metres.}$$

At its exit from the apparatus, *i.e.*, at the temperature $t_n = 36°$ and at $\frac{3}{4}$ saturation, the *volume*, V_{ln}, of the 4,076 kilos. of air is, by interpolation in column 5 of Table III.—

$$V_{ln} = \frac{4076}{1{\cdot}094} = 3725{\cdot}8 \text{ cubic metres.}$$

Finally, the necessary quantity of *heat* is obtained by means of equation (11)—

$$C_g = (4076 \times 0{\cdot}2375 + 15{\cdot}8 \times 0{\cdot}475)(100 - 0) = 97{,}655 \text{ calories.}$$

Tables IV., V. and VI. have been calculated in this manner.

TABLES IV., V. AND VI.

Weight and Volume of Air, Temperature of Exit and Expenditure of Heat required to evaporate 100 kilos. of water, when the external temperature is – 20° to + 30° C., the maximum temperature is 35°, 50°, 70°, 100° and 130° C., the external air is *completely saturated*, and the emergent air is only ¾, ½ or ¼ saturated with water vapour. Also expenditure of heat when the external air is ¾ saturated (see end of present chapter).

TABLE IV.

External air completely saturated. Emergent air is ¾ saturated.
Pressure in drying-room, $q = 760$ mm.

1	2	3	4	5	6	7	8	9	10
				Volume of the Air.				External Air ¾ Saturated.	
Temperature of the Saturated External Air, t_a.	Temperature of the Emergent Air, t_n.	Weight of the Dry Air, l.	Weight of the Moisture in the Air, ld_a.	At Entry, V_{la}.	After Heating, V_{lh}.	At Exit, $V_{lh'}$.	Expenditure of Heat, C_g.	Temperature of External Air.	Expenditure of Heat.
°C.	°C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.	°C.	Calories.
Maximum Temperature, $t_h = 35°$ C.									
– 20	14·6	12,720	9·7	9,158	11,108	10,316	166,408	– 25	152,162
0	18·6	15,720	60·8	12,256	13,499	13,123	130,763	– 5	113,151
15	24·75	24,300	262·4	20,250	21,384	20,770	116,640	10	89,424
20	27·25	37,040	548·2	31,470	32,595	32,200	133,344	15	91,860
25	30·75	71,430	1442·9	62,280	63,572	63,620	171,434	20	91,433
Maximum Temperature, $t_h = 50°$ C.									
– 20	21·0	9,000	6·87	6,478	8,229	7,561	149,849	– 25	139,769
0	24·0	9,823	38·0	7,655	9,026	8,367	117,550	– 5	106,549
15	28·5	12,500	135·0	10,424	11,625	11,062	105,875	10	90,875
30	38·0	20,412	561·0	18,274	19,460	18,896	102,275	25	67,187
Maximum Temperature, $t_h = 70°$ C.									
– 20	27·1	6,075	4·64	4,374	5,911	5,272	130,050	– 25	123,246
0	29·25	6,337	24·5	4,938	6,196	5,588	106,159	– 5	98,062
15	33·5	7,142	77·1	5,950	7,028	6,493	95,306	10	85,918
30	41·66	8,621	239·0	7,719	8,749	8,164	86,440	25	71,298
Maximum Temperature, $t_h = 100°$ C.									
– 20	35·25	3,963	3·02	2,853	4,193	3,608	113,113	– 25	108,675
0	36·0	4,076	15·8	3,176	4,334	3,726	97,655	– 5	93,090
15	39·5	4,130	45·9	3,540	4,561	4,000	87,361	10	82,265
30	45·75	4,505	123·9	4,034	4,968	4,383	79,013	25	73,450
Maximum Temperature, $t_h = 130°$ C.									
– 20	40·1	2,896	2·21	2,085	3,265	2,716	103,320	– 25	100,077
0	41·3	2,900	11·2	2,260	3,322	2,741	90,227	– 5	86,979
15	43·75	3,000	32·4	2,500	3,483	2,960	83,490	10	74,890
30	49·4	3,003	82·6	2,689	3,570	3,033	74,996	25	71,288

TABLE V.

External air completely saturated. Emergent air ½ saturated.
Pressure in drying-room, $q = 760$ mm.

1	2	3	4	5	6	7	8	9	10
Temperature of the Saturated External Air, t_a.	Temperature of the Emergent Air, t_n.	Weight of the Dry Air, l.	Weight of the Moisture in the Air, ld_a.	Volume of the Air.			Expenditure of Heat, C_g.	External Air ¾ Saturated.	
				At Entry, V_{la}.	After Heating, V_{lh}.	At Exit, V_{ln}.		Temperature of External Air.	Expenditure of Heat.
°C.	°C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres	Calories.	°C.	Calories.
Maximum Temperature, $t_h = 35°$ C.									
-20	17·75	15,151	11·56	10,907	13,231	12,621	198,212	-25	181,242
0	23·0	19,762	76·5	15,400	17,344	16,922	165,543	- 5	143,410
12·5	27·0	44,444	44·1	36,500	38,667	38,600	240,886	7·5	191,069
17·5	30·75	70,000	906·0	58,820	61,600	61,400	290,800	12·5	212,400
Maximum Temperature, $t_h = 50°$ C.									
-20	24·3	10,582	8·08	7,618	9,678	9,154	176,190	-25	164,339
0	28·25	11,736	45·32	9,146	10,784	10,210	140,441	- 5	127,712
30	44·2	42,553	1170·0	38,191	40,505	40,070	233,220	25	180,672
Maximum Temperature, $t_h = 70°$ C.									
-20	32·5	6,990	5·33	5,033	6,801	6,100	149,634	-25	141,866
0	35·25	7,463	28·9	5,832	7,297	6,711	123,262	- 5	114,904
30	47·5	10,753	295·7	9,628	10,906	10,329	107,768	25	94,460
Maximum Temperature, $t_h = 100°$ C.									
-20	40·1	4,366	3·33	3,144	4,619	4,010	124,621	-25	119,733
0	41·8	4,444	17·2	3,468	4,724	4,260	106,362	- 5	101,385
30	52·5	5,155	141·7	4,616	5,687	5,099	90,412	25	84,046
Maximum Temperature, $t_h = 130°$ C.									
-20	46·1	3,125	2·36	2,250	3,173	2,975	111,493	-25	107,993
0	47·5	3,135	12·1	2,443	3,592	3,006	97,500	- 5	93,989
30	56·5	3,309	90·75	2,963	3,923	3,358	82,685	25	78,599

TABLE VI.

External air completely saturated. Emergent air ¼ saturated.
Pressure in drying-room, q = 760 mm.

1	2	3	4	5	6	7	8	9	10
Temperature of the Saturated External Air, t_a.	Temperature of the Emergent Air, t_n.	Weight of the Dry Air, l.	Weight of the Moisture in the Air, ld_a.	Volume of the Air.			Expenditure of Heat, C_g.	External Air ¾ Saturated.	
				At Entry, V_{la}.	After Heating, V_{lh}.	At Exit, V_{ln}.		Temperature of External Air.	Expenditure of Heat.
°C	°C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.	°C.	Calories.
Maximum Temperature, t_h = 35° C.									
-20	24·5	24,940	18·93	17,955	21,721	21,234	326,271	-25	298,339
0	29·0	40,820	157·97	31,811	35,820	34,950	340,915	- 5	295,197
7·5	32·0	72,460	479·7	58,430	63,330	63,560	478,236	2·5	397,081
10	33·8	112,300	865·8	91,080	99,263	98,770	673,800	5	548,024
Maximum Temperature, t_h = 50° C.									
-20	32·3	14,760	11·26	10,626	13,496	12,028	245,749	-25	229,749
0	35·9	18,520	71·7	14,443	17,017	16,433	221,686	- 5	200,944
10	39·0	25,640	199·2	20,800	23,717	23,310	244,144	15	214,428
Maximum Temperature, t_h = 70° C.									
-20	41·75	8,873	6·77	6,400	8,633	8,067	189,445	-25	183,551
0	43·6	9,852	38·1	7,678	9,333	9,034	165,116	- 5	154,082
30	60·3	27,000	742·5	24,167	27,371	26,865	270,570	25	237,225
Maximum Temperature, t_h = 100° C.									
-20	50·3	5,263	4·02	3,789	5,568	4,990	150,223	-25	144,423
0	52·33	5,460	21·1	4,255	5,805	5,185	130,677	- 5	124,562
30	63·5	6,862	188·70	6,144	7,527	6,850	120,351	25	111,877
Maximum Temperature, t_h = 130° C.									
-20	58·5	3,600	2·75	2,620	4,104	3,575	94,193	-25	90,193
0	60·25	3,704	14·33	2,886	4,243	3,692	115,258	- 5	111,110
30	68·8	4,255	117·0	3,809	5,057	4,364	106,606	25	101,252

A comparison of Table II. (pp. 22-25) with Tables IV. (p. 35), V. (p. 36) and VI. (p. 37) shows that the necessary quantities of air and heat increase considerably with, though to a smaller extent than is proportional to, the decreasing degree of saturation of the emerging air; that the difference is least when the air is heated to a higher temperature, and greatest when the air is heated to a lower temperature; and that, with very warm external air and a low maximum temperature, no drying at all takes place, as is shown by the tables for maximum temperatures of 35° and 50° C. and an external temperature of 30° C.

In order that the alterations in the quantity of air, amount of heat and exit temperature, due to variations in the external temperature and in the highest temperature to which the air can be heated, may be seen at a glance, the accompanying Diagram II. has been plotted to represent the results of Table IV. The abscissæ represent external temperatures from − 20 to + 30° C., the ordinates give the values for the volumes of emergent air, V_{lm}, the exit temperature t_n, and the consumption of heat, C_g, the whole being given for five cases—*viz.*, when the highest air temperature, t_h, is 35°, 50°, 70°, 100° and 130° C. In every case the amount of water evaporated is 100 kilos.

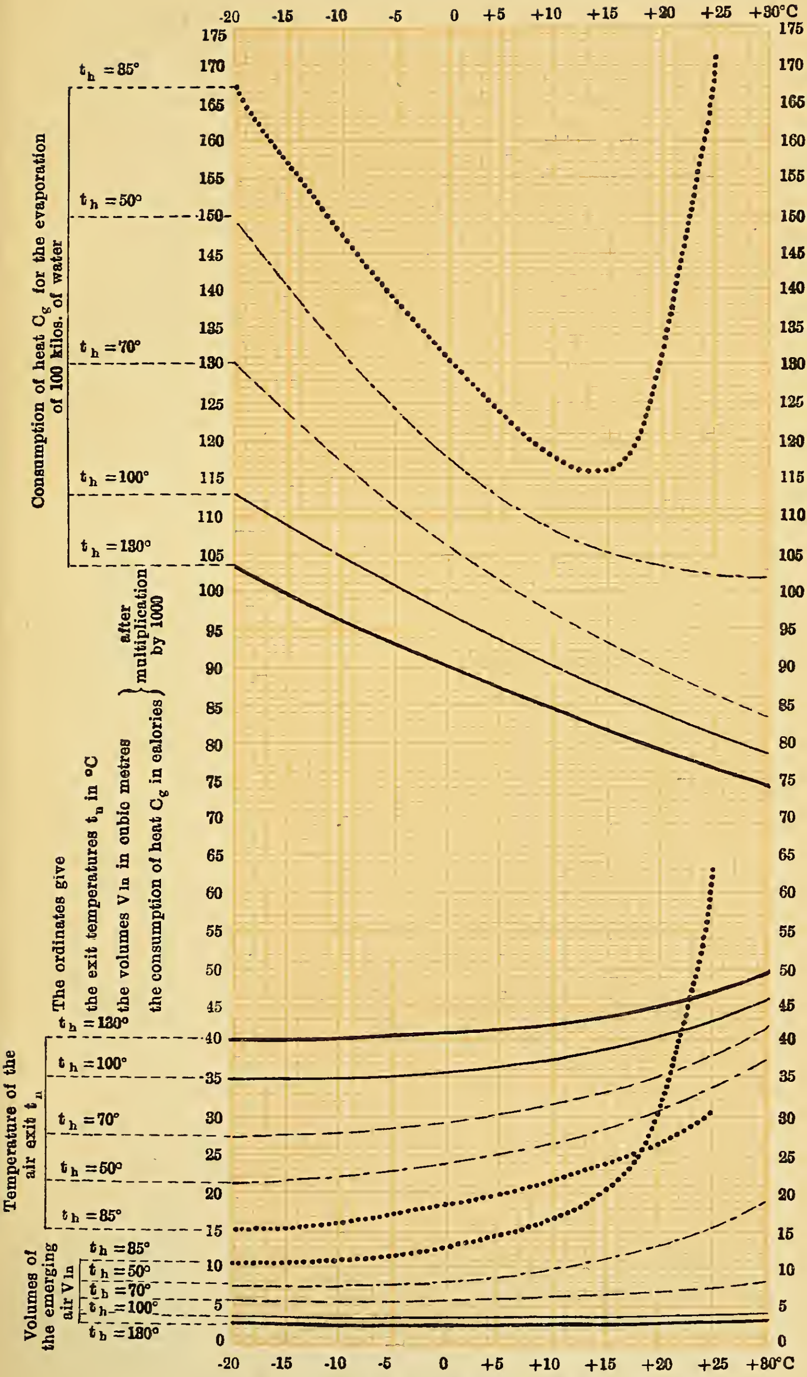
The ordinates give the exit temperatures in degrees Centigrade immediately, but in order to obtain the correct values for the emergent volume of air, V_{lm}, in cubic metres and the consumption of heat C_g, in calories, the ordinates must be multiplied by 1,000.

The curves are drawn in heavy, light, broken or dotted lines for the sake of distinctness, the curves relating to the same maximum temperature being always drawn in the same manner.

C.—*When the atmospheric air is* not *saturated with water vapour before entering the drying apparatus.*—Table VII.

When the air, before entering the drying apparatus, is not completely saturated with water vapour, 1 kilo. of the air

Diagram II.



Hausbrand's Drying by means of Air and Steam.

[illegible], 1 kilo. of the air

does not contain the maximum weight of water which it can retain at the particular temperature, but only as much as it can retain as a maximum at some lower temperature. For example, 1 kilo. of air at 15° C. can contain, when saturated, 0·0108 kilo. of water; if however 1 kilo. of air in a certain case contains only half as much, *viz.*, 0·0054 kilo., that is the maximum weight contained by 1 kilo. of saturated air at 5° C.

From Table I. (pp. 11-12) a compilation may be made showing the temperature at which air is completely saturated by a certain weight of water, and, further, the higher temperatures at which it would be only $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ saturated by the same weight of water.

TABLE VII.

Temperatures at which the Air would be Completely Saturated with Water if it is only $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ Saturated by the Same Quantity of Water at Certain Higher Temperatures.

		°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
Air which is completely saturated at . . .		– 20	– 15	– 10	– 5	0	+ 5	10	15	20	25	30
is, by the same quantity of water	$\frac{3}{4}$ saturated at	– 15	– 10	– 6·5	0	+ 5	10	15	20	25	30	35
	$\frac{1}{2}$,,	– 10	– 5	+ 1	+ 5	10	15	20	25	30	38	42
	$\frac{1}{4}$,,	– 5	0	+ 13	+ 15	20	25	32	38	43	50	55

Hence, when the air to be used for drying is not saturated at its present temperature with water vapour, that temperature at which it would be saturated by the same quantity of water per kilo. can readily be found by means of the Tables I. (pp 11-12) and VII. above.

In order to evaporate a definite weight of water there are required either x kilos. of atmospheric air at the temperature T_a, which contain y kilos. of water, by which the air is not saturated, or the same weight of air, x kilos., at the lower temperature t_a, which also contains y kilos. of water, by which, however, the air is completely saturated. The second quantity of air, when heated to the temperature T_a, is precisely in the same condition as the former quantity. Thus, in the former case, less heat is necessary in order to perform the same work, and the diminution in the heat required is the quantity necessary to heat x kilos. of air from t_a to T_a.

We shall now consider in what manner the results of the equations (7), (9) and (13) are altered when the external air is not saturated. In equation (9), by means of which the exit temperature of the air is determined, d_a, the weight of vapour in 1 kilo. of air at entry, will be smaller, and in fact only $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ as great as at complete saturation. We may also *suppose* that the air has *not* the temperature which it really has, but such a *lower* temperature that it is saturated by the same quantity of vapour d_a. This lower temperature is obtained from Table VII. (p. 39).

Example.—If the air is at 25° C. it can contain, as a maximum $d_a = 0{\cdot}0202$ kilo. of water in 1 kilo. when the barometer is at 760 mm. If it really contains only 0·01010 kilo., it is only half saturated. By this quantity of water ($d_a = 0{\cdot}01010$ kilo.) air at 15° C. would be completely saturated.

Since the initial temperature of the air does not affect equation (9), we obtain, by inserting the value of $d_a = 0{\cdot}01010$, both the temperature of the emerging air, t^n, and also its water-content, d_n, quite correctly, whatever may be the temperature of the external air. Both values are somewhat smaller than for $d_a = 0{\cdot}0202$.

The weight of air, l, is then found from equation (7) by inserting $d_a = 0{\cdot}01010$, and the value for t_n found from equation (9). The weight of air is also smaller than for $da = 0{\cdot}0202$.

The volume V_{la}, of the correct weight of outside air, l, which is saturated at 15° C., is somewhat smaller than it would be at 25° C. if $\frac{1}{2}$ saturated. The difference is not very great, and need hardly be considered, since in a drying apparatus the air should be pumped as it leaves the apparatus and not as it enters.

The volumes of the heated air, V_{lh}, and of the emergent air, V_{lm}, are estimated from their weight and temperature. Both factors are the same in each case, whether $\frac{1}{2}$ saturated air at 25° C. or saturated air at 15° C. is introduced, and hence the volumes are the same.

The quantity of heat, C_g, required to warm the air, is obtained from equation (13), in which, t_a, the external temperature occurs. We have seen that the results given by equations (7) and (9) (outlet temperature, weight and volumes) for air which is not saturated at a certain temperature are almost exactly the same as the results to be found in Tables II. (pp. 22-25), IV. (p. 35), V. (p. 36) and VI. (p. 37) for completely saturated air of a lower temperature. With the expenditure of heat it is different. This is smaller by the quantity of heat required to bring the air from its temperature of saturation (in the example, 15° C.) to its real temperature, t_a, at which it is not saturated (in the example, 25° C.). The consumption of heat, C_g, is thus only $\dfrac{t_h - T_a}{t_h - t_a}$ of the quantity required by the air at its (lower) temperature of saturation. Thus in calculating the leading dimensions for a drying apparatus, the assumptions made in Tables II., IV., V. and VI., that the air is completely saturated before it enters the heating chamber, will not be followed, but another and smaller degree of saturation of the external air will be assumed. For this purpose less than 50 per cent. of saturation should not be taken; 75 per cent. is better. Tables II., IV., V. and VI. may then be used, working in the following manner:—

From Table VII. (p. 39) that temperature is found at which the air would be saturated when at its real temperature, t_a, it is only $\frac{3}{4}$, $\frac{1}{2}$ or $\frac{1}{4}$ saturated. Then, in Tables II., IV., V. or VI.

(according as it is assumed that the emergent air is completely [II.], ¾ [IV.], ½ [V.] or ¼ [VI.] saturated), by means of the lower temperature of saturation obtained from Table VII., the correct temperature of exit is found in column 2, the correct weight of air, *l*, in column 3, the volume of external air (a little too small) in column 5, and the correct volumes of the air after heating and on leaving the apparatus, V_{lh} and V_{lm}, in columns 6 and 7.

Air, which at a certain temperature is completely saturated, is, as is seen from Table VII. (p. 39) for the temperatures to be considered here, ¾ saturated by the same quantity of water when it is about 5° hotter, ½ saturated when about 10° hotter, and ¼ saturated when about 15° hotter. Thus no great error will be made if the decrease in the consumption of heat be taken as equal to the heat required to warm the air through 5° C. (*i.e.*, $l \times 5 \times 0{\cdot}2375$) for ¾ saturation, through 10° C. (*i.e.*, $l \times 10 \times 0{\cdot}2375$) for ½ saturation, and through 15° C. (*i.e.*, $l \times 15 \times 0{\cdot}2375$) for ¼ saturation. The results are not altered by more than 0·5 to 5 per cent. by reason of the unequal water-content of the air, so that in most cases a correction on this account may be neglected.

Thus if it is to be assumed that the external air before it enters the heating chamber of the drying apparatus is not completely saturated with moisture, as is assumed in the main portion of Tables II., IV., V. and VI., but only ¾ saturated, the temperature of the ¾ saturated external air will be found in column 9 of Tables IV. V. and VI., and the real consumption of heat in column 10 of the same tables.

Example.—100 kilos. of water are to be evaporated by means of external air at 30° C., which is only ¾ saturated, under the assumption that the emergent air is completely saturated. The maximum temperature, $t_h = 50°$ C.

According to Table VII., air which is only $\frac{3}{4}$ saturated at 30° C. is completely saturated at 25° C. by the same quantity of water.

In Table II. are found, under the maximum temperature t_h = 50° C. with t_a = 25° C., the desired figures for air completely saturated at 25° C., which hold good unaltered for air $\frac{3}{4}$ saturated at 30° C., *viz.*, the exit temperature, t_n = 30° C., the weight of air, l = 13,700 kilos., the weight of moisture, ld_a = 276·74 kilos., the volume of entering air, V_{la} = 11,970 cubic metres, the volume of heated air, V_{lh} = 12,845 cubic metres, and the volume of emerging air, V_{ln} = 12,267 cubic metres.

The consumption of heat must be calculated. It is equal to that given in the table = 80,625 calories, less $l\ (0·2375 + d_a\ 0·475)\ 5 = 5\ (13,700 \times 0·2375 + 276·7 \times 0·475)$ = 16,925 calories, *i.e.*, the total consumption of heat = 80,625 − 16,925 = 63,700 calories.

CHAPTER IV.

Drying Apparatus in which, in the Drying Chamber, a Pressure higher or lower than that of the Atmosphere is artificially maintained.—Tables VIII., IX. and X.

The question which has now to be considered is what advantage there is in artificially diminishing or increasing the pressure in the drying-room. From what has preceded it is clear that when the pressure in the drying-room is considerably higher than that of the atmosphere, 1 cubic metre of air cannot contain more saturated water vapour at the same temperature than when under normal pressure. The higher pressure in the interior is not due to a higher pressure of the vapour, but only to a greater pressure of the air; the same volume of air at the same temperature is only able to contain the same weight of saturated water vapour at every pressure, since the pressure of saturated vapour in the air depends only upon the temperature and not upon the total pressure.

If the pressure in a space be artificially increased by the introduction of air, without change of temperature, then air and vapour gradually mix and the space contains, at the final pressure, the original weight of vapour together with the additional air. If the vapour were removed from the space, the pressure would sink by an amount equal to the pressure of the vapour; but if it were desired to force in vapour, this could only be done by increasing the temperature, otherwise the additional vapour would condense. Thus, when there is a higher pressure in the drying-room, a greater weight of air must be used in order to evaporate a given weight of water. Since this greater weight of air must be previously heated, it follows that the apparatus consumes more heat than when working under normal pressure.

In Table I., columns 13, 14 and 15, have already been given the necessary data for the calculation of the dimensions of such an apparatus to work at an excess-pressure of $\frac{1}{2}$ atmosphere (= 1,140 mm.). Column 13 gives the pressure the air would have alone, without the vapour, at temperatures from − 20° to + 100° C. and at a total pressure of 1,140 mm. Column 14 gives the weight of 1 cubic metre of air under the same conditions, and in column 15 is shown the weight of saturated vapour in 1 kilo. of air.

Equations (7) and (9) may be used in the calculation of the weight of air and temperature of exit necessary to evaporate a given weight of water; for d_a the values given in Table I., column 15, must be used.

The necessary weights and volumes of air and the exit temperatures have been calculated by means of these equations and arranged in Table VIII. (p. 50), *viz.*, for the evaporation of 100 kilos. of water with the external temperature − 20°, 0° or + 30° C., and with the air heated to 35°, 50°, 70°, 100° and 130° C.

It may be seen clearly from Table VIII. (p. 50) how much more air and heat are used for a definite drying capacity when a higher pressure than that of the atmosphere is artificially maintained in the interior of the drying-room. Thus such an arrangement is not advantageous in practice.

In regard to Table VIII., it should also be observed that a limit is placed on the working of the apparatus by certain external temperatures when there is a higher pressure in the interior; for if the atmospheric air is hot and saturated with moisture, the condition may arise in which the air compressed into the interior alone effects the pressure, and there remains no place for the vapour. One kilo. of air of a definite volume conveys into the apparatus a certain volume of moisture. In the apparatus this weight of air should be able to take up a further definite volume of moisture, but since it now occupies a smaller volume than formerly, it may happen that this volume is less than is required by its original moisture. This is seen in Table VIII. at the maximum temperature of 35° C.: external air saturated with moisture at 30° C., when compressed to 1½ atmospheres (absolute) pressure, cannot take up as much vapour as it can evaporate by giving out heat. This limit is almost attained by external air at 25° C. saturated with moisture.

The case is quite different when a diminished pressure is artificially maintained in the drying-room. This arrangement is advantageous in practice. There is said to be diminished pressure (a partial vacuum) in a space when it contains a smaller weight of air than at the atmospheric pressure. The weight of saturated vapour, which this space can contain at a certain temperature, is independent of the presence or absence of air, and is always the same for the same temperature. Thus, under diminished pressure, a space contains more saturated vapour per unit weight of air than space under ordinary or increased pressure.

It follows that a weight of air, smaller than under other conditions, is sufficient under diminished pressure to take up the same quantity of water, but that this smaller weight of air must give up the same quantity of heat in order to evaporate the same weight of water, and must thus leave the drying-room cooler, and, finally, that the total consumption of heat by this method will be less than in a room at the ordinary pressure.

Table I. already contains, in columns 16 to 21, the preliminary figures for the calculation of the cases in which there is a vacuum of 510 or 260 mm. in the drying-room, *i.e.*, when there is an absolute pressure of 250 or 500 mm. The calculations are based upon the equations (7) and (9); the value for d_n is taken from column 18 or 21.

Example.—One hundred kilos. of water are to be evaporated with the maximum temperature of the air $t_h = 70°$ C., the external temperature $t_a = 0°$ C., and with the absolute pressure $q = 500$ mm. in the drying-room. It is required to calculate the temperature of exit t_n, the requisite weight of air, l, its volume before entry, V_{la}, after heating, V_{lh}, at exit, V_{ln}, and the consumption of heat, C_g.

In equation (9) are to be inserted—

$$t_h = 70, \qquad d_a = 0{\cdot}00387 \text{ (Table I., column 11)}, \qquad w = 100,$$
$$C_n = 62{,}500.$$

Thus the right-hand side becomes—

$$\frac{62{,}500}{100\,(0{\cdot}2375 + 0{\cdot}00387 \times 0{\cdot}475)} = 2616.$$

The left-hand side of the equation gives, after making trial insertions of various values from Table I., column 18, for $d_n = 0{\cdot}0230$ (at $t_n = 20°$ C.)—

$$\frac{70 - 20{\cdot}1}{0{\cdot}0230 - 0{\cdot}00387} = 2612.$$

Thus the temperature of the exit, $t_n = 20°$ C.

The weight of air is obtained from equation (7)—

$$l = \frac{w}{d_n - d_a} = \frac{100}{0{\cdot}0230 - 0{\cdot}00387} = 5{,}235 \text{ kilos.}$$

The weight of the original moisture (ld_a) in this air is—

$$ld_a = 5235 \times 0{\cdot}00387 = 20{\cdot}2 \text{ kilos.}$$

The volume of the outside air, V_{la}, is—

$$V_{la} = \frac{5{,}235}{1{\cdot}2832} = 4{,}075 \text{ cubic metres.}$$

The volume of the air when heated to 70° C. is—

$$V_{lh} = \frac{273 + 70}{10{,}336\frac{500}{760}} (29{\cdot}27 \times 5{,}239 + 46{\cdot}83 \times 20{\cdot}2) = 7{,}782 \text{ cubic metres.}$$

The volume of the emergent air is—

$$V_{ln} = \frac{5{,}235}{0{\cdot}765} = 6{,}843 \text{ cubic metres.}$$

Finally, the amount of heat required to warm the air is—

$$C_g = (5{,}235 \times 0{\cdot}2375 + 20{\cdot}2 \times 0{\cdot}475)\,(70 - 0) = 87{,}640 \text{ calories.}$$

In Tables IX. (p. 51) and X. (p. 52) are given the weights and volumes of air, the temperature of the emergent air, and the consumption of heat necessary to evaporate 100 kilos. of water, when the external temperature is − 20°, 0° and + 30° C., and the temperature of the hot air is 35°, 50°, 70°, 100° and 130° C. In comparison with the figures of Table II., a diminution, in part considerable, is observed in the consumption of heat and the weight of air.

It will also be remarked that, with diminished pressure in the interior of the drying apparatus and warm outside air, the quantity of heat required to evaporate 100 kilos. of water is less than 62,500 calories, *i.e.*, less than the quantity of heat theoretically necessary to evaporate 100 kilos. of water. An absolute pressure of 500 mm. (260 mm. vacuum) already effects this (Table IX.) when the maximum temperature is 35° C., and the outside temperature 30° C.; but the effect is more striking at the absolute inner pressure of 250 mm. (500 mm. vacuum), as seen in Table X., at which in all cases a high external temperature gives rise to considerable economy in heat.

The reason for this effect is easily understood. The atmospheric air, which enters the apparatus at a higher temperature (30° C.) and leaves it at a much lower, has given up a portion of its natural heat, which thus does not require to be artificially added to it; this, then, is a gain. In the cases in which the conditions are so favourable that it is only necessary to heat a considerable quantity of air through a very small range of temperature in order to bring it up to its permissible maximum temperature, this large quantity of air leaves the apparatus considerably colder than it entered, and thus the whole of the heat given up by the air in cooling from the external temperature to the temperature of exit is utilised in evaporation without expense.

From a theoretical standpoint, apparatus in which drying is done *in vacuo* is thus to be recommended on all grounds, but the great atmospheric pressure exerted upon the walls of the drying-room at any considerable vacuum, and the porosity of the materials from which the apparatus is to be constructed, offer practical difficulties.

Since Tables IX. and X. are calculated for completely saturated entering and for completely saturated emergent air, additions must be made for less favourable conditions, the magnitude of which may be estimated by a comparison of the figures of Tables II., IV., V. and VI.

TABLES VIII., IX. AND X.

The Weight and Volume of Air, Temperature of Exit and Expenditure of Heat required to evaporate 100 kilos. of water when the external temperature is – 20°, 0° and + 30° C., the maximum temperature is 35°, 50°, 70°, 100° and 130° C., and *both* external and emergent air are *completely saturated* with water vapour.

VIII. The absolute pressure is 1,140 mm. ($1\frac{1}{2}$ atmos.).
IX. ,, ,, ,, 500 ,,
X. ,, ,, ,, 250 ,,

TABLE VIII.

External and emergent air completely saturated. Pressure in drying-room q = 1,140 mm. ($\frac{1}{2}$ atmos. over normal).

1	2	3	4	5	6	7	8
				Volume of the Air.			
Temperature of External Air, t_a. °C.	Temperature of the Emergent Air, t_n. °C.	Weight of the Dry Air, l. Kilos.	Weight of the Moisture in the Air, ld_a. Kilos.	At Entry, V_{la}. Cubic Metres.	After Heating, V_{lh}. Cubic Metres.	At Exit, V_{ln}. Cubic Metres.	Expenditure of Heat, C_g. Calories.
Maximum Temperature, t_h = 35° C.							
– 20	16·5	14,300	10·91	10,280	8,318	7,665	187,000
0	19·75	17,240	66·6	12,464	10,077	9,860	144,410
+ 30	—	—	—	—	—	—	—
Maximum Temperature, t_h = 50° C.							
– 20	22·0	9,430	7·2	6,782	5,760	5,341	157,010
0	25·0	10,500	40·6	7,591	6,443	5,947	125,650
+ 30	39·75	25,000	687·6	22,385	15,920	14,750	125,540
Maximum Temperature, t_h = 70° C.							
– 20	28·0	6,235	4·75	4,480	4,039	3,554	131,470
0	30·75	6,666	25·8	4,819	4,339	3,933	111,650
+ 30	43·75	9,260	257·8	8,292	6,251	5,538	92,960
Maximum Temperature, t_h = 100° C.							
– 20	36·0	4,085	3·1	2,935	2,904	2,395	116,604
0	37·5	4,180	16·2	3,022	2,986	2,849	100,100
+ 30	47·5	4,760	130·9	4,261	3,527	2,856	83,300
Maximum Temperature, t_h = 130° C.							
– 20	41·5	2,930	2·22	2,014	2,230	1,758	104,750
0	42·5	3,000	11·61	2,170	2,294	1,840	93,210
+ 30	51·0	3,205	88·14	2,870	2,543	1,955	80,200

TABLE IX.

External and emergent air completely saturated. Pressure in drying-room, $q = 500$ mm. (= 260 mm. vacuum).

1	2	3	4	5	6	7	8
Temperature of External Air, t_a.	Temperature of the Emergent Air, t_n.	Weight of the Dry Air, l.	Weight of the Moisture in the Air, ld_a.	Volume of the Air.			Expenditure of Heat, C_g.
				At Entry, V_{la}.	After Heating, V_{lh}.	At Exit, V_{ln}.	
°C.	°C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.
Maximum Temperature, t_h = 35° C.							
− 20	8·75	10,000	7·63	7,184	13,260	12,662	130,790
0	11·25	10,950	42·4	7,916	14,588	12,900	91,756
+ 30	25·2	25,000	687·5	22,385	34,557	34,065	31,385
Maximum Temperature, t_h = 50° C.							
− 20	13·0	7,143	5·44	5,135	9,941	9,085	118,930
0	15·5	7,559	35·2	5,465	10,585	10,400	90,500
+ 30	27·33	11,000	302·5	9,850	15,962	15,135	55,240
Maximum Temperature, t_h = 70° C.							
− 20	18·0	5,000	3·82	3,597	7,390	6,698	107,010
0	20·1	5,235	20·2	4,075	7,782	6,843	87,640
+ 30	30·25	6,250	171·8	5,596	9,630	6,825	62,800
Maximum Temperature, t_h = 100° C.							
− 20	24·0	3,440	2·62	2,473	5,511	4,665	98,280
0	25·5	3,505	13·6	2,534	5,643	4,875	83,800
+ 30	33·75	3,816	104·9	3,417	6,376	5,264	66,920
Maximum Temperature, t_h = 130° C.							
− 20	29·25	2,470	1·89	1,795	4,288	3,286	88,200
0	29·75	2,602	10·1	1,884	4,540	3,575	80,990
+ 30	36·75	2,700	74·25	2,418	4,888	4,150	74,360

TABLE X.

External and emergent air completely saturated. Pressure in drying-room, $q = 250$ mm. (= 510 mm. vacuum).

1	2	3	4	5	6	7	8
Temperature of External Air, t_a.	Temperature of the Emergent Air, t_n.	Weight of the Dry Air, l.	Weight of the Moisture in the Air, ld_a.	Volume of the Air.			Expenditure of Heat, C_g.
				At Entry, V_{la}.	After Heating, V_{lh}.	At Exit, V_{ln}.	
°C.	°C.	Kilos.	Kilos.	Cubic Metres.	Cubic Metres.	Cubic Metres.	Calories.
Maximum Temperature, $t_h = 35°$ C.							
− 20	1·5	7,874	6·0	5,660	20,875	20,152	108,515
0	3·75	8,403	32·5	6,082	22,414	20,543	70,350
+ 30	15·75	12,820	352·6	11,480	35,447	33,272	25,920
Maximum Temperature, $t_h = 50°$ C.							
− 20	5·5	5,900	4·5	4,239	16,403	14,514	98,280
0	7·25	6,060	23·5	4,383	16,826	15,310	72,500
+ 30	17·75	8,130	223·57	7,280	23,512	21,010	40,820
Maximum Temperature, $t_h = 70°$ C.							
− 20	9·5	4,340	3·31	3,120	12,817	11,480	92,880
0	11·0	4,464	17·2	3,230	13,241	11,500	74,760
+ 30	20·25	5,000	127·5	4,478	15,284	12,642	50,000
Maximum Temperature, $t_h = 100°$ C.							
− 20	14·6	3,033	2·31	2,167	9,716	8,056	86,640
0	16·0	3,102	12·0	2,243	10,008	8,116	74,200
+ 30	23·0	3,280	90·2	2,937	10,905	9,144	57,470
Maximum Temperature, $t_h = 130°$ C.							
− 20	18·75	2,381	1·8	1,711	8,260	6,362	75,050
0	19·75	2,385	9·2	1,724	8,299	6,240	74,100
+ 30	25·75	2,400	66·0	2,149	8,582	6,917	60,000

CHAPTER V.

Drying by means of superheated Steam, without Air.—Table XI.

It is possible to go a step further and eliminate air from the drying-room altogether, so that the drying then takes place by means of vapour (steam) alone. Let us consider the air drawn from the drying-room, *T*, as shown diagrammatically in Fig. 2, by a fan, *F*, or other apparatus for moving gases, and again forced over the heating surfaces, *H*, at the entry to the drying-room. Thus the mixture of air and vapour goes through a complete cycle of operations, which carry it from the fan to the heater, from the latter into the drying chamber, thence to the fan and so on. The whole apparatus is to be supposed tightly closed, and as far as possible protected against loss of heat.

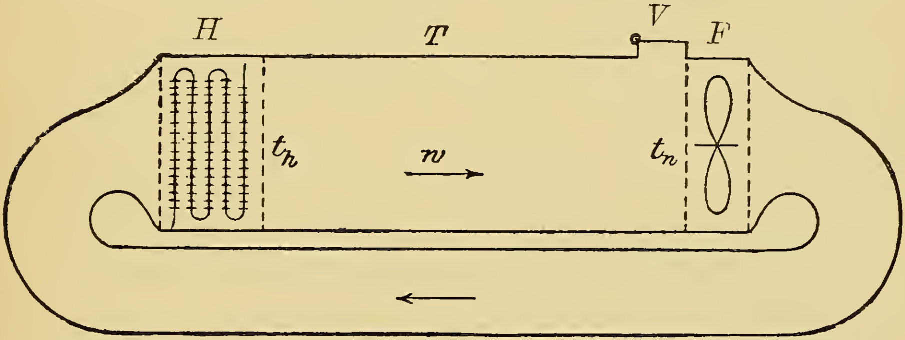


Fig. 2.

Between the exit from the drying chamber and the entrance into the fan is a valve, *V*, opening outwards, which allows air and vapour to pass into the atmosphere as soon as the pressure in the interior exceeds a predetermined limit. If the apparatus be closed and the fan set in motion, the mixture of air and vapour goes through the cycle of movements indicated above, and thus becomes hotter and hotter; consequently it takes up more and more moisture, and thus the internal pressure increases continuously until it is sufficient to open the valve and so permit air and vapour to escape.

If the air and vapour be continuously circulated, air and vapour escape continuously through the valve, until finally there is no longer any air in the apparatus; then steam alone is contained in the interior and escapes regularly through the valve into the atmosphere. Thus the drying apparatus is now working without air and by means of steam (vapour) alone.

The steam, compressed by the fan, is superheated by the heating surfaces, enters the drying-room, and there becomes saturated by water taken from the wet material. Its pressure rises, and a portion, *viz.*, that which corresponds to the water absorbed from the wet material, escapes through the valve.

If the dried material be continually removed and fresh wet material introduced, the apparatus works continuously, and contains only as much air as is unavoidably introduced together with the fresh material.

The consumption of heat in such an apparatus, apart from losses due to leakage and radiation, is theoretically exactly equal to the heat required to heat the material to the prevailing temperature *plus* that necessary to evaporate the water, and thus is the least possible. This method of construction is, therefore, economically the best, leaving out of consideration the rare cases mentioned on p. 48.

It would be most simple and natural to load the valve only to such an extent that the pressure in the interior was but little higher than the atmospheric pressure, so that the temperature at which the water evaporated was very little above 100° C. However, it might be desirable for some reason or another to change this pressure so that it should be higher or lower than that of the atmosphere.

A higher pressure is obtained by a greater load on the valve, so that it resembles a safety valve which opens at a pre-determined pressure. In regard to practical applications, regard must be given to the pressure upon the internal wall of the apparatus and to the high temperature to which the material is exposed.

If the temperature in this air-free process is to be maintained below 100° C., the construction is made more difficult, since the pressure in the drying-room must then be lower in proportion to the temperature. This lower pressure necessitates special arrangements. In the first place, air and vapour will not pass spontaneously from the drying-room into the atmosphere; they must be extracted by means of an air-pump, and extracted continuously, since in practice air will always be found to leak in. Since, however, all machines for the production of high vacua do not satisfactorily withdraw the vapour at the same time, on account of its great volume, it is necessary to condense the vapour either by a direct spray of water or by means of a surface condenser. Thus the operation of drying is made more expensive.

If, however, all these arrangements are provided, the water in the drying-room may be evaporated by means of superheated steam at any low pressure. It would indeed be somewhat difficult to move the attenuated vapours in their circuit by means of the fan, on account of their great volume, but the possibility of this method of working is certain.

It is well known that the presence of air in steam hinders considerably the transference of its heat, either for purposes of heating or in cooling and condensation. In practice steam used for boiling or heating, or which is to be condensed, is kept as free as possible from air, for only in this condition is obtained the greatest transference of heat by 1 square metre of contact surface. This is a further reason for preferring drying apparatus from which air is removed to the greatest possible extent, since the heating surface for heating the vapour and the cooling surfaces, by which it is finally condensed, then have the least area.

In order to obtain an idea of the weight and volume of steam required to evaporate $w = 100$ kilos. of water at various drying-room pressures, some important cases will at once be calculated. As we have already seen, apart from loss, the expenditure of heat is equal to the theoretically necessary amount, *i.e.*, if the material to be dried enters the apparatus at 15° C.—

$$C_g = (640 - 15)\, w = 62{,}500 \text{ calories} \quad . \quad . \quad . \quad . \quad (14).$$

The weight of superheated steam, D, required to evaporate w kilos. of water, is obtained from a consideration of the fact that the heat required to evaporate w kilos. of water must be equal to the heat the steam can give out in cooling from the temperature at which it is superheated down to the temperature prevailing in the apparatus. Thus we obtain—

$$C_g = w\,(640 - 15) = D\, s\, (t_h - t_n) \quad . \quad . \quad . \quad . \quad (15).$$

in which

D = the weight of superheated steam in kilos.
s = the specific heat of steam at constant pressure = 0·475.
t_h = the maximum temperature.
t_n = the temperature prevailing in the drying-room.

Example.—$w = 100$ kilos. of water are to be evaporated, the maximum temperature $t_h = 110°$, the temperature of evaporation in the apparatus $t_n = 100°$.

By equation (15)—

$$D \times 0{\cdot}475\,(110 - 100) = 100\,(640 - 15) = 62{,}500 \text{ calories,}$$

or

$$D = 13{,}157 \text{ kilos.}$$

The weight of steam, D, must be led over the material to be dried in order to effect the desired evaporation. The volumes V_{dn} and V_{dh} of this steam, before and after heating, are obtained by means of the general equation (12)—

$$\frac{V}{273 + t} = R, \qquad \text{or} \qquad V = \frac{R\,(273 + t)}{p},$$

in which t = the temperature, R = the constant = 46·83 for superheated steam (according to G. Schmidt), V = the volume of 1 kilo. of steam, p = pressure of the steam expressed in kilos. per square metre. At atmospheric pressure $p = 10{,}336$; at any other pressure q expressed in millimetres of mercury (equation 4)—

$$p = \frac{10{,}336\,q}{760}.$$

The volume of the heated steam is—

$$V_{dh} = \frac{D\ 46{\cdot}83\,(273 + t_h)}{\frac{10{,}336\,q}{760}} \quad . \ . \ . \ . \ . \ . \quad (16).$$

The volume of the steam before superheating is—

$$V_{dn} = \frac{D\ 46{\cdot}83\,(273 + t_n)}{\frac{10{,}336\,q}{760}} \quad . \ . \ . \ . \ . \ . \quad (17).$$

Example.—For the case last mentioned $p = 10{,}336$, $t_h = 110$, $t_n = 100$, therefore—

$$V_{dh} = \frac{D\ 46{\cdot}83\,(273 + 110)}{10{,}336} = 1{\cdot}735 \times 13{,}157 = 22{,}827 \text{ cubic metres.}$$

$$V_{dn} = \frac{D\ 46{\cdot}83\,(273 + 100)}{10{,}336} = 1{\cdot}689 \times 13{,}157 = 22{,}422 \text{ cubic metres.}$$

TABLE

The Weights of Steam and their Volumes, before and after Heating, Apparatus, without Air, at absolute pressures of 148 to

	Temperature of Interior,	t_n =	60°	75°	90°
	Absolute Pressure, mm.		148	288	525
	Vacuum, mm.		612	472	235
t_h = 65° C.	Weight of steam	D =	26,315	—	—
	Volume ,, before heating	V_{dn} =	201,528	—	—
	,, ,, after ,,	V_{dh} =	206,843	—	—
t_h = 70° C.	Weight of steam	D =	13,158	—	—
	Volume ,, before heating	V_{dn} =	101,245	—	—
	,, ,, after ,,	V_{dh} =	105,001	—	—
t_h = 75° C.	Weight of steam	D =	8,778	—	—
	Volume ,, before heating	V_{dn} =	67,630	—	—
	,, ,, after ,,	V_{dh} =	70,997	—	—
t_h = 80° C.	Weight of steam	D =	6,579	26,316	—
	Volume ,, before heating	V_{dn} =	52,954	111,054	—
	,, ,, after ,,	V_{dh} =	54,027	107,790	—
t_h = 85° C.	Weight of steam	D =	5,263	13,158	—
	Volume ,, before heating	V_{dn} =	40,714	56,316	—
	,, ,, after ,,	V_{dh} =	43,836	54,005	—
t_h = 90° C.	Weight of steam	D =	4,386	8,778	—
	Volume ,, before heating	V_{dn} =	34,224	38,097	—
	,, ,, after ,,	V_{dh} =	37,017	36,563	—
t_h = 95° C.	Weight of steam	D =	3,760	6,579	26,316
	Volume ,, before heating	V_{dn} =	29,448	28,948	63,527
	,, ,, after ,,	V_{dh} =	32,816	27,357	61,474

XI.

required to Evaporate 100 kilos of Water in the Circuit Drying
2,660 mm. and with maximum temperatures of 65° to 200° C.

	$t_n =$	100°	110°	120°	130°	140°
Absolute Pressure	mm.	760	1,064	1,520	2,090	2,660
	Atmospheres	1	1·4	2·0	2·75	3·5
t_h = 110° C. . .	D =	13,157	—	—	—	—
	V_{dn} =	22,422	—	—	—	—
	V_{dh} =	22,827	—	—	—	—
t_h = 120° C. . .	D =	6,579	13,157	—	—	—
	V_{dn} =	10,876	15,933	—	—	—
	V_{dh} =	11,447	17,696	—	—	—
t_h = 130° C. . .	D =	4,386	6,579	13,157	—	—
	V_{dn} =	7,237	7,967	10,315	—	—
	V_{dh} =	7,807	9,079	11,605	—	—
t_h = 140° C. . .	D =	3,473	4,386	6,579	13,157	—
	V_{dn} =	5,730	5,311	5,658	8,394	—
	V_{dh} =	6,321	6,197	5,947	8,605	—
t_h = 150° C. . .	D =	2,632	3,473	4,386	6,579	13,157
	V_{dn} =	4,343	4,206	3,772	4,197	6,684
	V_{dh} =	4,922	6,174	4,057	4,408	6,842
t_h = 160° C. . .	D =	2,193	2,632	3,473	4,386	6,579
	V_{dn} =	3,618	3,187	2,987	2,798	3,342
	V_{dh} =	4,145	3,901	3,269	3,004	3,500
t_h = 180° C. . .	D =	1,644	1,879	2,193	2,632	3,473
	V_{dn} =	2,613	2,275	1,886	1,679	1,764
	V_{dh} =	3,288	2,912	2,173	1,887	1,939
t_h = 200° C. . .	D =	1,299	1,531	1,644	1,879	2,193
	V_{dn} =	2,143	1,854	1,414	1,199	1,114
	V_{dh} =	2,715	2,480	1,702	1,405	1,303

In Table XI. are given the weights of steam, D, and their volumes, V_{dh} and V_{dn}, required to evaporate 100 kilos. of water, working at atmospheric pressure, at pressures less than atmospheric (148, 288 and 525 mm.), and at pressures greater than atmospheric (1·4, 2, 2·75 and 3·5 atmospheres absolute). From Table XI. it will be seen that the volumes of vapour to be moved at very low pressures are very great, which is in no way the case at atmospheric or higher pressures, so that the volume to be moved is not then a hindrance in this method of drying.

CHAPTER VI.

Heating Surface, Velocity of the Air Current, Dimensions of the Drying-room, Surface of the Drying Material, Losses of Heat.—Tables XII. and XIII.

In this chapter will be considered some not unimportant details of the drying apparatus. The area of the heating surface, H, in square metres, is conditioned by the mean difference in temperature, t_m, between the air and the hot surface and the co-efficient of transmission, k. The latter depends upon the velocity, c metres per second, with which the air passes over the hot surface. It is expressed by an equation deduced by Molier from the experiments of others—

$$k = 2 + 10\sqrt{c} \quad . \quad . \quad . \quad . \quad . \quad . \quad (18).$$

The *area of the heating surface* for the transference of C_g calories of heat per hour is—

$$H = \frac{C_g}{t_m\,(2 + 10\sqrt{c})} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19).$$

The greater the velocity of the air current over the heating surface, the more heat it takes up. Accordingly, it would be advantageous to make the air move very rapidly, but, as we shall see, the velocity ought not to be too high.

The *temperature difference* between the air and the heating surface depends upon the mean temperatures of the surface and of the air. The cooler is the air originally, the greater is the mean difference in temperature and the higher is the efficiency of the heating surface. Since the drying apparatus frequently requires the greatest quantities of heat when the external air is cold, the last-mentioned circumstance is in many cases a fortunate coincidence.

In Table XII. are given the differences in temperature between the heating surface and the air. Since the atmosphere has very different temperatures at different seasons, the difference in temperature between the heating surface of the same apparatus and the air also varies greatly, although the former is always maintained at the same temperature. Thus in column 4 are given the mean differences when the external temperatures are – 20°, 0°, 15° and 30° C., the constant temperature of the heating surface is 100°, 120° and 140° C. in each case, and the highest temperature the air may attain is 35°, 50°, 70°, 100° or 130° C.

Also in the same table, in columns 5, 6, 7 and 8, are given the quantities of heat, calculated by means of equation (19), which can be communicated by 1 square metre of a smooth iron heating surface in one hour, when the air moves over it with velocities of 1, 2, 4 or 6 metres per second. By means of this table may be found the heating surface necessary in each case by dividing the proper figure in Table XII., column 5, 6, 7 or 8, into the figure which gives the number of calories to be used in one hour. If ribbed heating bodies be used instead of smooth iron pipes, Table XII. may still be used, but, before dividing, the figures in columns 5, 6, 7 and 8 must be multiplied by 0·7.

The air should not pass too rapidly through the drying-room. The resistance of the air, due to friction in passing through pipes and flues, increases with its velocity, therefore a rapid current of air necessitates more power for, and gives rise to a smaller output of, the fan.

Flues conveying air to and from the heating chamber may generally be omitted. In case they have to be inserted the velocity of the air in them should not exceed 3 metres per second, and if possible should be less.

TABLE XII.

The Quantities of Heat given up by 1 square metre of the source of Heat in one hour when the external air is at – 20° to + 30° C., the source of heat is at 100° to 140° C., the heated air is at 35° to 130° C., and the air current passes over the heating surface with a velocity of 1 to 6 metres per second.

1	2	3	4	5	6	7	8
Temperature of the Heated Air, t_h. °C.	Temperature of the Source of Heat, t_c. °C.	Temperature of the External Air, t_a. °C.	Mean difference in Temperature, t_m. °C.	Amount of Heat, in Calories, given out by 1 Sq. Metre of the Heating Surface in 1 Hour when the Air passes over it with a Velocity of			
				1 Metre Per Sec.	2 Metres Per Sec.	4 Metres Per Sec.	6 Metres Per Sec.
35	100	– 20	92	1,104	1,372	2,024	2,437
,,	,,	0	82	984	1,312	1,804	2,238
,,	,,	+ 15	75	900	1,200	1,650	2,017
,,	,,	+ 30	67	804	1,072	1,474	1,774
50	,,	– 20	85	1,020	1,370	1,870	2,311
,,	,,	0	75	900	1,200	1,650	2,017
,,	,,	+ 15	67	804	1,072	1,474	1,774
,,	,,	+ 30	60	720	960	1,320	1,589
70	,,	– 20	75	900	1,200	1,650	2,017
,,	,,	0	65	780	1,040	1,430	1,602
,,	,,	+ 15	55	660	886	1,210	1,456
,,	,,	+ 30	50	600	800	1,100	1,325
35	120	– 20	112	1,344	1,792	2,464	2,966
,,	,,	0	102	1,224	1,632	2,244	2,701
,,	,,	+ 15	95	1,140	1,520	2,090	2,516
,,	,,	+ 30	87	1,044	1,392	1,914	2,304
50	,,	– 20	105	1,260	1,680	2,310	2,781
,,	,,	0	95	1,140	1,520	2,090	2,516
,,	,,	+ 15	87	1,044	1,392	1,914	2,304
,,	,,	+ 30	80	960	1,280	1,760	2,179
70	,,	– 20	95	1,140	1,520	2,090	2,516
,,	,,	0	85	1,020	1,370	1,870	2,311
,,	,,	+ 15	77	924	1,232	1,694	2,149
,,	,,	+ 30	70	840	1,120	1,540	1,954
100	,,	– 20	80	960	1,280	1,760	2,123
,,	,,	0	70	840	1,120	1,540	1,854
,,	,,	+ 15	62	744	992	1,364	1,642
,,	,,	+ 30	55	660	880	1,210	1,456

[*Continued on p.* 64.

TABLE XII. (*Continued*).

1	2	3	4	5	6	7	8
Temperature of the Heated Air, t_h. °C.	Temperature of the Source of Heat, t_c. °C.	Temperature of the External Air, t_a. °C.	Mean Difference in Temperature, t_m. °C.	Amount of Heat, in Calories, given out by 1 Sq. Metre of the Heating Surface in 1 Hour when the Air passes over it with a Velocity of			
				1 Metre Per Sec.	2 Metres Per Sec.	4 Metres Per Sec.	6 Metres Per Sec.
35	140	− 20	132	1,584	2,102	2,904	3,497
,,	,,	0	122	1,464	1,952	2,684	3,231
,,	,,	+ 15	115	1,380	1,834	2,530	3,046
,,	,,	+ 30	107	1,284	1,712	2,354	2,834
50	,,	− 20	125	1,500	2,000	2,750	3,310
,,	,,	0	115	1,380	1,840	2,530	3,046
,,	,,	+ 15	108	1,296	1,728	2,376	2,866
,,	,,	+ 30	100	1,200	1,600	2,200	2,649
70	,,	− 20	115	1,380	1,840	2,530	3,046
,,	,,	0	105	1,260	1,680	2,310	2,781
,,	,,	+ 15	97	1,164	1,552	2,134	2,569
,,	,,	+ 30	90	1,080	1,440	1,980	2,384
100	,,	− 20	100	1,200	1,600	2,200	2,649
,,	,,	0	90	1,080	1,440	1,980	2,384
,,	,,	+ 15	82	984	1,312	1,804	2,238
,,	,,	+ 30	75	900	1,200	1,650	2,017
130	,,	− 20	54	648	871	1,188	1,323
,,	,,	0	49	588	790	1,078	1,200
,,	,,	+ 15	46	552	742	1,012	1,127
,,	,,	+ 30	42	504	677	922	1,029

The area of *the transverse section of the heating chamber* is diminished by the heating bodies, thus the air passes over the latter with a somewhat greater velocity, which should not be allowed to exceed 6 metres per second even in this place.

In the drying-room itself a slow motion of the air is necessitated, since it does not immediately become saturated with moisture. A certain interval, not too brief, is required, so that the water vapour may diffuse with the air.

It is advisable to conduct the air through the drying-room in such a manner that it passes over the material divided into currents which are frequently changed. The material should also be spread out so that it is uniformly surrounded on all sides by the air which warms and dries it. The greatest velocity of the air in the drying-room should be 6 metres per second, and, if possible, less.

The arrangements, upon which the material in the drying-room is carried, spread out or hung, must be so large or so numerous that they can take as much material as corresponds with the product of the time required to dry a single article or portion multiplied by the contemplated drying output. Thus, if a single article or portion requires two days to dry sufficiently, and if 1,000 articles or kilos. are to be dried in one day, the drying-room must have space for at least 1,000 × 2 = 2,000 articles or kilos.

The *time*, which one article or portion of the material requires to dry sufficiently, cannot, generally speaking, be estimated beforehand, since it depends to a considerable extent upon the nature of the particular material. The initial and final proportions of moisture, the thickness, shape and the greater or less capacity for transferring the internal moisture rapidly to the surface, influence the time required for drying.

When a moist substance is surrounded by warm air not saturated by moisture, in motion or at rest, the position is almost exactly the same in regard to the expected evaporation of water as if it were in a partial vacuum, *i.e.*, under diminished pressure. In warm air, not saturated by vapour, the vapour is indeed at the same temperature as the air, but has not the pressure proper to it at that temperature. It is capable and desirous of taking up the offered moisture until it is saturated, *i.e.*, until its pressure corresponds to the temperature. This absorption of moisture does not however take place immediately, but requires a certain length of time, and this all the more since the fresh vapour to be taken up must displace the air in the place of which it steps.

The heat, which must be supplied to the drying material for the evaporation of its moisture, can only enter through the surface, and, other conditions being the same, the quantity of heat which enters will be proportional to the surface. Thus the material to be dried should expose the greatest possible surface to the air current.

The quantity of heat transferred to the material is however also proportional to the mean difference in temperature between air and drying material. The place, at which the material at temperature t_u enters, is also the place at which the air at temperature t_n leaves. Thus the difference in temperature at this point is $t_n - t_u$. At the exit of the dried material the hot air enters at the temperature t_h. The dried material leaves several degrees cooler than the hot air enters; the exact difference depends on the particular circumstances. We will call the temperature of the dried material t; the difference in temperature is therefore $t_h - t_z$. If we assume that the temperature difference $t_h - t_z$ is at least half as great as $t_n = t_u$, then the mean difference in temperature—

$$t_m = \frac{(t_h - t_z) + (t_n - t_u)}{2}.$$

For the case in which $t_h - t_z$ is less than $\frac{t_n - t_u}{2}$ the mean difference in temperature is less than the arithmetic mean.*

Example.—If the highest temperature to which the air may be heated is $t_h = 100°$, the outlet temperature of the air $t_n = 36°$, the temperature at which the material enters $t_u = 15°$, at which it leaves $t_z = 30°$, the mean difference in temperature is *not*—

$$\frac{(100 - 30) + (36 - 15)}{2} = \frac{70 - 21}{2} = 45{\cdot}5°.$$

---

* See Hausbrand's, *Evaporating, Condensing and Cooling Apparatus*, published by Messrs. Scott, Greenwood & Son (London).

but is, according to the source quoted in the footnote (Table I.), since $\frac{21}{70} = 0{\cdot}3$—

$$t_m = 0{\cdot}583 \times 70 = 40{\cdot}81^\circ.$$

Finally, as we know, the velocity c, with which the air passes over the drying material, exerts an influence upon the quantity of heat transferred. The co-efficient of transmission—

$$k = 2 + 10\sqrt{c}.$$

Thus the quantity of heat to be transferred in one hour to the drying material is—

$$C_n = O \cdot t_m \cdot k = O \cdot t_m (2 + 10\sqrt{c}),$$

where O represents the surface area of the drying material, in square metres, across which C_n calories are to be conveyed. Thus—

$$O = \frac{C_n}{t_m (2 + 10\sqrt{c})} \quad . \; . \; . \; . \; . \; . \; . \quad (20).$$

From this equation we can now calculate the surface which must be exposed to the air current in order to evaporate a certain quantity of moisture in one hour.

Example.—100 kilos. of water are to be evaporated in one hour. The air passes over the material with a velocity of $c = 4$ metres per second, its temperature is at first $t_h = 50^\circ$, finally $t_n = 25^\circ$ C. The material is at first at $t_u = 15^\circ$, finally at $t_z = 30^\circ$ C. Then—

$$t_m = \frac{(t_h - t_z) + (t_n - t_u)}{2} = \frac{(50 - 30) + (25 - 15)}{2} = 15^\circ.$$

Thus the surface of the drying material must be—

$$O = \frac{62{,}500}{15\,(2 + 10\sqrt{4})} = 190 \text{ square metres (approx.).}$$

The results of these equations cannot be applied in every case, since the physical properties of the material to be dried may cause the transference of heat not to take place exactly according to the principles enunciated above. In such cases experience is the only guide.

The air always enters the drying-room hotter than it leaves, and although in several cases its degree of saturation with water vapour may be greater at its entry than its exit, yet the higher temperature at which it enters always causes the density of the air at entry to be less than at exit. It has therefore an inclination to pass downwards. In vertical drying-rooms the direction of the currents of air should therefore be from top to bottom, since the movement is then more uniform than when the hot air enters below and at

TABLE XIII.

Losses of Heat, in Calories, by Drying Apparatus in one hour from 1 square-metre of Masonry, Wooden Wall or Simple Window at temperature differences between interior and exterior of 5° to 100° C.

Difference in Temperature between Interior and Exterior. °C.	Thickness of Masonry Walls.						Wooden Wall.	Simple Window.
	120 mm.	250 mm.	380 mm.	510 mm.	640 mm.	770 mm.		
5	12	8·5	6·5	5·5	4·5	4	11	25
10	24	17·0	13·0	11·0	9·0	8	22	50
15	36	25·5	19·5	16·5	13·5	12	33	75
20	48	34·0	26·0	22·0	18·0	16	44	100
25	60	42·5	32·5	27·5	22·5	20	55	125
30	72	51·0	39·0	33·0	27·0	24	66	150
35	84	59·5	45·5	38·5	31·5	28	77	175
40	96	68·0	52·0	44·0	36·0	32	88	200
45	108	76·5	58·5	49·5	40·5	36	99	225
50	120	85·0	65·0	55·0	45·0	40	110	250
55	132	93·5	71·5	60·5	49·5	44	121	275
60	144	102·0	78·0	66·0	54·0	48	132	300
65	156	110·5	84·5	71·5	58·5	52	143	325
70	168	119·0	91·0	77·0	63·0	56	154	350
75	180	127·5	97·5	82·5	67·5	60	165	375
80	192	136·0	104·0	88·0	72·0	64	176	400
85	204	144·5	110·5	93·5	76·5	68	187	425
90	216	153·0	117·0	99·0	81·0	72	198	450
95	228	161·5	123·5	104·5	85·5	78	209	475
100	240	170·0	130·0	110·0	90·0	80	220	500

once takes the shortest path to the upper exit without coming in contact with all the drying material. Similarly in drying in flues the air should also leave below.

We have seen that in drying apparatus, which works at a high temperature, losses by cooling through the walls and masonry must be avoided as far as possible. The magnitude of this loss is indicated in Table XIII., which gives the number of calories lost in one hour from 1 square metre of masonry or wooden wall of various thicknesses.

It may be mentioned here that, in certain cases, when the apparatus works at a low temperature and at a very small internal pressure, the interior may be cooler than the surrounding air. In this event the apparatus takes up heat from its surroundings to its advantage, and it would be advisable to construct its walls in such a manner that they would readily transmit heat to the interior.

Thus, whilst a drying apparatus intended to work at a high temperature should be constructed of masonry with an insulating layer of air, apparatus required to work at a low temperature should be made with thin wooden or metal walls.

In all cases the drying-room must be protected against the entry of air from outside. The walls must always be free from leaks, otherwise cold air would enter the drying-room of apparatus working at high temperatures and moist air would enter apparatus working at low temperatures.

THE END.

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